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Sources of dissociation in the forgetting trajectories of implicit and explicit knowledge

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Zusammenfassung

Die vorliegende Dissertation untersucht Dissoziationen zwischen Vergessensverläufen für implizites und explizites Wissen. Aus diesem Ansatz können sich wesentliche Einschränkungen ergeben in Bezug auf die Annahme, sowohl impliziten als auch expliziten Prozessen liege ein einziges Gedächtnissystem oder ein einziger Mechanismus zugrunde.

Im theoretischen Teil der Arbeit wird implizites Wissen als Information definiert, die ohne Intention gelernt und abgerufen wird, und die generelle Bedeutung einfacher Dissoziationen für Theorien impliziten Wissens erklärt. Ich gebe einen Überblick über die wesentlichen Forschungsprogramme in Hinblick auf Funktionen, Prozesse, Entwicklung, neuronale Korrelate und Vergessensverläufe impliziten Wissens und lege dar, daß der Vergleich der Vergessensverläufe impliziten und expliziten Wissens eine graduelle Perspektive ermöglicht, die die mit an einem einzelnen isolierten Zeitpunkt beobachteten einfachen Dissoziationen verbundenen Probleme überwindet, und auch dazu beitragen kann, die Lücke zwischen der Forschung zum impliziten Lernen und zum impliziten Gedächtnis zu schließen.

In einer Reihe von vier Experimenten wurden studentische Versuchsteilnehmer Regelhaftigkeiten in der Umwelt ausgesetzt, die in eine künstliche Grammatikaufgabe (AG) oder Wahlreaktionsaufgabe (SRT) eingebettet waren. Für den Vergleich der Vergessensverläufe wurde das implizite (aus motorischen Reaktionszeiten erschlossene) und explizite (auf Wiedererkennung basierte) Wissen der Versuchspersonen jeweils vor und nach einem Behaltensintervall erfaßt. Die Befunde zeigen, daß sowohl in der AG als auch der SRT explizites Wissen schneller zerfällt als implizites. Darüber hinaus lieferte eine Interferenz-Aufgabe, die anstelle des Behaltensintervalls eingesetzt wurde, das gleiche Dissoziationsmuster.

Schließlich wurde anhand einer Reihe von Simulationen geprüft, ob ein komputationales Ein-Speicher-Modell (Shanks, Wilkinson, & Channon, 2003) die experimentellen Befunde erklären kann. Die Simulationen zeigen, daß das Modell nur dann in Übereinstimmung mit den Daten gebracht werden kann, wenn zwischen den verschiedenen Meßzeitpunkten Veränderungen in den Parametern (a) der

gemeinsamen Repräsentationsstärke für implizites und explizites Wissen, und (b) der Reliabilität des expliziten Maßes eingeführt werden.

Meine Dissertation schlägt also (1) einen konzeptuellen Rahmen für explizites und implizites Wissen vor, erbringt (2) neue empirische Belege für Dissoziationen zwischen den Vergessensverläufen dieser Wissensformen, und identifiziert (3) die spezifischen Randbedingungen für ein Ein-Speicher- bzw. Ein-Prozess-Modell.

Schlagwörter:

Implizites Gedächtnis, Implizites Lernen, Vergessen, Interferenz, Dissoziation

Abstract

In this dissertation I investigate dissociations in the forgetting patterns of implicit and explicit knowledge. I claim that this approach may provide significant constraints for the assumption that a single system or mechanism determines both implicit and explicit processes.

In the theoretical part, I construe a definition of implicit knowledge as information learned and retrieved without intention. I also explain the general role of single dissociations in theories of implicit knowledge. And I present an overview of the main lines of research concerned with the functions, operation, development, neural substrates, and forgetting patterns of implicit knowledge. In general, I argue that comparing the forgetting patterns of implicit and explicit knowledge may be best regarded from a graded perspective and may usefully bridge the gap between research on implicit learning and implicit memory.

In a series of 4 Experiments university students were exposed to environmental regularities embedded in artificial grammar (AG) and serial reaction time (SRT) tasks. To compare the forgetting patterns, participants' implicit (motor-performance based) and explicit (recognition based) knowledge was assessed before and after a retention interval. Taken together, the results indicate that explicit knowledge decays faster than implicit knowledge in both AG and SRT tasks. Furthermore, an interference task introduced instead of a retention interval produced the same pattern of dissociations.

Finally, I conducted a set of simulations to asses the ability of a single-system model (Shanks, Wilkinson, & Channon, 2003) to account for my experimental results. The simulations showed that the model best fits the empirical data by introducing changes in the parameters related to (a) the common knowledge strength (for implicit and implicit knowledge), and (b) the reliability for the explicit test.

In sum, my dissertation (1) suggests a conceptual framework for implicit and explicit knowledge, (2) provides new empirical evidence of dissociations in their forgetting patterns, and (3) identifies specific boundary conditions for a single-system model.

Keywords:

Implicit memory, implicit learning, forgetting, interference, dissociation

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List of Abbreviations

AG	Artificial Grammar
ANOVA	Analysis of Variance
CRT	Cathode-Ray Tube
d’	d-prime
dREC	Discriminability of Recognition Ratings
dRT	Discriminability in Reaction Time
FA	False Alarms
ms	Milliseconds
MSe	Mean Square Error
PRS	Perceptual Representation System
REM	Rapid Eye Movement
RSI	Response Stimulus Interval
RT	Reaction Time
SOC	Second Order Conditional (Sequence)
SRT	Serial Reaction Time
SWS	Slow Wave Sleep

1 Introduction

Knowledge enables adaptation, that is, learners use their experience with previous situations to cope with new and old environmental demands. Sometimes the knowledge is intentionally acquired and is accompanied by awareness of having learned a certain skill or concept. Some other times, however, people may learn spontaneously and behave adaptively without consciously intending to apply previously acquired knowledge. For example, an adult may need explicit instruction on grammar and syntax to learn a second language. On the other hand, a child may learn and display implicit knowledge of her native tongue by successfully communicating with others without explicitly knowing any grammatical rules.

Psychologists have proposed a distinction between implicit and explicit systems to describe and explain these two forms of knowledge acquisition and processing. Versions of this distinction have emerged in most fields of contemporary scientific psychology such as perception (MacLeod, 1998), learning (Reber, 1993), memory (Schacter, 1987), reasoning (Evans, 2003; Sloman, 1996), emotion (Damasio, 1996; Winkielman and Berridge, 2004) and personality (Asendorpf, 2007). Researchers on implicit learning and memory share an interest in explaining how implicit knowledge may be acquired, represented, and stored in memory (Dienes and Perner, 2000). In particular, research on implicit learning seeks to identify the processes that enable incidental or unintentional acquisition of skills and information (Frensch, 1998; Shanks, 2005). In turn, research on implicit memory attempts to understand how information can be automatically retrieved without conscious intervention (Graf and Masson, 1993; Roediger, 1990). These aspects have been intensively investigated in the laboratory and have become cornerstones in the characterization of implicit processing in general (Berry and Dienes, 1993; Cleeremans and French, 2002; Graf and Masson, 1993; Jiménez, 2003; Kirsner, et al., 1997; Reber, 1993; Stadler and Frensch, 1998).

However, from the beginning, the distinction between explicit and implicit processing has also been the focus of intense and complex debates. Mainly, between proponents of the idea that implicit and explicit processing should be regarded as an indivisible entity (e.g., Ratcliff and McKoon, 1996; Shanks, 2005) and proponents of idea that these processes should be regarded as the result of multiple underlying systems (e.g., Reber, 1993; Schacter, et al., 2000). Three main issues have been recurrent in the discussion on implicit learning and implicit memory: (1) How to establish adequate conceptual and operational criteria to define implicit and explicit knowledge? (2) How comparable are implicit and explicit tests and what kind of knowledge do they tap? (3) Which criteria are suitable to conjecture independent cognitive systems? A current dominant view concerning the first issue, posits that it is essential to look for commonalities among different research programs and to try to make evident the underlying concepts and operational definitions from the experimental procedures employed in different paradigms (e.g., Cleeremans, 1997; Frensch, 1998).

Concerning the second issue (the impurity of implicit and explicit measures), a debate in progress advocates that implicit and explicit tests may simultaneously tap diverse processes and possibly have different sensitivities. For instance, it seems realistic to assume that recognition tests primarily (but not exclusively) tap explicit knowledge whereas motor or perceptual tests predominantly tap implicit knowledge, and therefore, it appears tenable to assume that different tasks differ in the reliability with which the underlying knowledge is assessed (e.g., Buchner and Wippich, 2000; Jiménez, et al., 1996; Reingold and Merikle, 1990; Shanks and St John, 1994).

Regarding the third issue (criteria to conjecture an implicit system), it is currently assumed that converging evidence about the nature of dissociations between implicit and explicit tests across a broad range of manipulations and research domains is required (e.g., Ashby and Ell, 2002; Dunn and Kirsner, 1988; Squire, 2004). More importantly, it has been suggested that besides mere dissociations between measures of implicit and explicit knowledge collected at one isolated point in time, research must also provide insights into (a) temporal dynamics of the knowledge-base, and (b) specific processes that generate dissociations in order to have better criteria to decide between single and multiple-system accounts (Frensch and Runger, 2003; Munakata, 2001).

Indeed, explorations of the temporal dynamics of information (i.e., gradual consolidation and degradation) seem to be needed because in most contemporary conceptions of learning and memory, knowledge is no longer regarded as a binary phenomenon that is either present or absent. More reasonably, knowledge is currently regarded as a graded phenomenon (e.g., Cleeremans and Jiménez, 2002; Munakata, 2001; van Gelder, 2000). An important consequence of this assumption is that at a certain level, some information may display correlations between implicit and explicit measures but at some other level may display dissociations.

Specific processes (being specific mechanisms or modules) need also additional study because neither can dissociations provide exhaustive evidence for dual-system accounts nor are correlations conclusive for inferring single-systems. On the one hand, dissociations may be produced by some single-system processes but on the other hand, it is logically plausible that correlations observed at one isolated moment may also be mimicked by two different underlying systems. In other words, dissociations per se are not necessarily very informative about the possible mechanisms that produce them.

Consider that at an earlier point in time a single memory trace displays a *correlation* between explicit and explicit tests. For instance, when the strength of the memory trace is above both the implicit and the explicit thresholds. At a later point in time, however, the same memory trace, degraded by the passage of time or by interference, displays a *dissociation* because it is detected by the lower threshold but not detected by the higher threshold (e.g., Norman, 1969). This illustrates the idea that the temporal dynamics of knowledge, namely, the comparison of at least two different points in time may be complemented with a specific mechanism, different thresholds, in order to account for dissociations.

The continuing debate has made it clear that no single experiment or series of experiments is likely to tell us whether dissociations between implicit and explicit knowledge are the result of the operation of a single or dual system or process. Rather, what appears to be needed is a host of research aimed at different key aspects (e.g., functions, operating principles, neural substrates, development patterns, etc.) of implicit and explicit forms of knowledge that, in the end, may lead to a unifying theory. Additionally, some researchers have started to claim that a graded approach might be productive to resolve the debates around single and dual perspectives on implicit processes (e.g., Cleeremans and Jiménez, 2002).

One promising key aspect that might be useful to understand the nature of dissociations between explicit and implicit knowledge concerns the direct comparison of retention rates for implicit and explicit information. For instance (to return to the example from the first paragraph), most second-language learners forget their explicit grammatical knowledge unless they constantly practice it. But even after a long retention interval without practice, many people would implicitly display proficient knowledge of their native language. Indeed, it is generally assumed that without rehearsal, explicit knowledge is relatively fragile whereas implicit knowledge is relatively stable over time (e. g., Willingham & Dumas, 1997). For example, it is widely believed that once someone learns to ride a bicycle, the implicit or procedural knowledge involved in this skill will never be forgotten.

Despite the fact that differences in forgetting patterns of implicit and explicit knowledge have not been conclusively explored in the laboratory (Roediger and McDermott, 1993), everyday experience seems to show that explicit knowledge is forgotten sooner than implicit knowledge. This commonsense insight might be significant for understanding implicit cognition in general. On one hand, if it is reliably shown that implicit knowledge is in fact better retained than explicit knowledge, then the argument could be made that this difference in retention of information is due to a fairly different form of processing. It could be argued that implicit knowledge is at some point in time differently acquired, represented, or retrieved by the cognitive system. Actually, within the field of memory research, proponents of very dissimilar frameworks agree in that evidence of different forgetting patterns represents a relevant a priori criterion to postulate independent, multiple-memory systems (Dosher and Rosedale, 1991; McBride and Dosher, 1997; Nadel, 1994; Schacter and Tulving, 1994). On the other hand, if it is assumed that both implicit and explicit knowledge derive from a unitary memory system (e.g., Kinder and Shanks, 2001; Kinder and Shanks, 2003; Shanks, et al., 2003), then this perspective would be further supported by evidence showing that implicit and explicit knowledge are forgotten at similar rates.

The focus of the present dissertation is therefore on *comparing the forgetting rates of implicit and explicit knowledge*. One fundamental point of departure of this work is the idea that endorsing a graded perspective, by studying the temporal dynamics of knowledge, might be useful for understanding the sources of dissociation between implicit and explicit tests. In particular, I ask whether explicit knowledge about environmental regularities embedded in artificial grammars (Chomsky and Miller, 1965) and stimulus-sequences (Nissen and Bullemer, 1987) decays more rapidly than implicit knowledge of the same materials. I also ask whether this difference might be accounted for by a widely studied and relatively well understood mechanism of forgetting such as *interference* (Altmann and Gray, 2002; Deffenbacher, et al., 1981; Mensink and Raaijmakers, 1988; Wixted, 2005).

As mentioned above, the question about how qualitatively different memory traces (implicit vs. explicit) change over time is especially relevant to identify empirical constraints that may contribute to decide between multiple-systems (e.g., Schacter, et al., 2000) or single-system (e.g., Nosofsky and Zaki, 1998) perspectives on memory. Simultaneously, because this approach assumes a graded perspective, it may constitute a strategy that overcomes some logical difficulties in the formulation of dissociable systems based on single dissociations. Another advantage is that this tactic demands consistency between processes of learning and memory. That is, if learning may feed memory with implicit knowledge then it should follow that memories may also be implicit. This particular characteristic makes this question of interest for research on implicit learning (Reber, 1967; Reber, 1989) and for understanding processes of information representation (Dienes and Perner, 2000; Schacter and Tulving, 1994; Vokey and Higham, 2000).

One of the main reasons I became excited about comparing the forgetting patters of implicit and explicit knowledge was that the above sketched argument seemed very straightforward, in short: if implicit and explicit knowledge about the same database display different forgetting patterns, then it should follow that they are governed by different systems or processes. However, I soon realized that current notions of multiple systems (e.g., Squire, 2004) are open to many interpretations and are not likely to be easily falsified by any corpus of data. Specially, because the quest for classifications of memory faces not only the difficult task of providing empirical evidence for multiple-systems approaches but also confronts the challenge of (1) performing conceptual analyses to clarify the explanatory power of taxonomies (c.f., Willingham and Goedert, 2001), (2) clarifying the relationship between systems and functions (e.g., Bowers and Kouider, 2003), and (3) defining basic concepts such as “system” or “implicit knowledge”. These conceptual ambiguities have led to many misunderstandings in the past; for example, treating descriptive terms as hypothetical constructs, equating experimental procedures with cognitive processes, confounding the assumed representation-contents with functions of hypothesized systems, etc. Against this background, I also find it relevant to devote some effort not only to establish a “state of the art” of the empirical lines of research on implicit memory and learning but also to attempt to construct a coherent conceptual framework to warrant the experiments and simulations of the empirical section.

I begin this dissertation by presenting the basic concepts that support research on implicit processes. I provide theoretical and operational definitions for both implicit learning and implicit memory, and show how the broader concept of *implicit knowledge* may link them together. I elaborate then the concept of *dissociation* and the concept of *system,* and identify a set of basic criteria that are used to support the assumption of multiple systems of memory. In this first chapter, I also point out why studying the forgetting patterns of implicit and explicit knowledge might be regarded as a potentially productive alternative to evidence of single dissociations observed at one isolated point in time. Finally, I finish the chapter on basic concepts by presenting the multiple-systems and the single-system perspectives.

In Chapter 2, I summarize the empirical evidence according to the criteria offered to warrant the postulation of multiple-systems perspectives. For example, I identify open questions regarding differences in the functioning, development, and neural substrates of implicit and explicit systems. Finally, I focus on previous research that has specifically compared the temporal dynamics of implicit and explicit knowledge.

The empirical chapters of this dissertation have three main parts. First, I tackle the study of forgetting (Experiments 1 and 2) and interference (Experiment 3) of implicit and explicit knowledge in artificial grammar tasks. In the introduction to Experiment 3, I revisit concepts and evidence of *interference,* which I regard as one likely candidate mechanism to account for dissociations in forgetting patterns of explicit and implicit knowledge. What distinguishes decay from interference? How does the interplay among factors such as consolidation, forgetting, and different forms of knowledge work? How can the effects of interference be methodologically separated from the effects of decay? This discussion clarifies the potential role that interference may play in dissociating the forgetting patterns of implicit and explicit knowledge.

In the second part of the empirical section, I extend the findings of Experiments 1 and 2, conducted with artificial grammars, to other environmental regularities such as those incorporated into the Serial Reaction Time (SRT) Task. In Experiment 4A, I replicate the main features of an experiment that has been taken as evidence of a single-system model (Shanks, et al., 2003) and apply the logic of observing different forgetting patterns by measuring implicit and explicit knowledge after a retention interval of 7 days. In Experiment 4B, I further evaluate the forgetting patterns of implicit and explicit knowledge up to a retention interval of 100 days.

Finally, in the third empirical part, I evaluate the ability of a computational single-system model (Shanks, et al., 2003) to simulate the empirical data obtained in the previous sections.

2 Basic Concepts

In this chapter, I present the basic concepts that support the dissertation and explain how they are concretized in the empirical part. First, I elaborate on the concept of *implicit knowledge* and argue for a definition that ought to involve research on both implicit learning and implicit memory. Second, I explain (a) the conditions that *dissociations* between measures of implicit and explicit knowledge should fulfill to be considered a valid index of different underlying systems, and (b) how a graded perspective may help to fulfill these conditions. Third, the focus is on clarifying the concept of *system* by distinguishing it from related concepts such "process" or "forms" of memory, and by identifying a set of fundamental criteria that have been taken to justify the postulation of different learning and memory systems. These criteria are particularly important because I use them to organize the bulk of empirical evidence in Chapter 3. Finally, after a short historical outline, I present the key concepts surrounding the multiple-systems view and the single-system view.

2.1 Implicit knowledge

In ordinary language, *implicit* refers to something that is conveyed but not directly expressed. Ordinary language and folk psychology allow for two meanings of implicit knowledge. The first meaning refers to information contained in the nature of *nonverbal* behavior by inferring knowledge from performance. For instance, when a passenger infers that a taxi driver has a good knowledge of the city because she is able to find the shortest route to some destination. The second meaning of implicit knowledge refers to *additional* information extracted from some already explicit verbalizations. For instance, in the utterance "I did not see you yesterday at the meeting", a sensitive listener may infer that the speaker is complaining, although that is not the utterance's primary explicit message.

Experimental psychology has focused mainly on the first meaning of implicit knowledge, that is, on knowledge inferred from performance (Frensch, 1998; Roediger, 2003). Three aspects of implicit knowledge have been thoroughly investigated, (1) the information-processing stages attributed to the cognitive system: learning, storage, and retrieval, (2) the role of awareness: either accompanied by awareness or without awareness, and (3) the form of knowledge representation: either abstract or specific. Different combinations of these aspects may usefully characterize similarities and differences among several definitions. A rigorous definition would posit, for instance, that knowledge is implicit if it is (A) incidentally acquired, (B) abstractly held in memory, and (C) unintentionally retrieved; where attribute A refers to the learning stage, attribute B refers to the storage stage, and attribute C refers to the retrieval stage. Accordingly, the stringency of any definition mainly depends on whether these characteristics are mutually or exclusively required. For example, one of the earliest definitions claimed that implicit knowledge should satisfy conditions A and B (Reber, 1969; Reber, 1989), but later research demonstrated that criterion B may not be essential because successful performance on transfer tests of implicit knowledge may be explained on the basis of information contained in specific instances or fragments of the learned material (Perruchet and Pacteau, 1990).

Criteria derived from the processing stages in combination with the role of awareness are also useful to trace a conceptual boundary between research on (1) implicit learning, which has predominately focused on incidental acquisition of knowledge (Stadler and Frensch, 1998), and (2) implicit memory, which has mainly focused on unintentional retrieval of information (Roediger, 1990; Squire, et al., 1993). The boundary between implicit learning and implicit memory reflects, of course, different research interests and paradigms, fundamentally the fact that knowledge acquisition does not need to be incidental in implicit memory tasks (Buchner and Wippich, 1998). However, researchers are starting to recognize that more connections between research on memory and learning processes such as object identification, conceptualization, and categorization have to be achieved in order to understand implicit knowledge processes in general (Bowers and Marsolek, 2003).

2.1.1 Acquisition of implicit knowledge

The acquisition of implicit knowledge has been conceptualized in at least two major ways. The first way emphasizes the acquisition of knowledge without *intention* (e.g., Neal and Hesketh, 1997; Whittlesea and Dorken, 1997), for example by comparing participants' performance instructed to search for environmental regularities versus performance of participants not informed about any environmental regularity. The second major way to define implicit learning is related to the lack of *attention* for knowledge acquisition (e.g., Jimenez and Mendez, 1999;

e.g., Seger, 1994). For example, when participants are required to perform an additional task that distracts them from the primary learning task (Frensch, et al., 1994; Shanks and Channon, 2002).

2.1.2 Representation of implicit knowledge

How is implicit knowledge represented and stored? This question had been largely addressed within the scope of research on both implicit learning and implicit memory. The answer to this question has taken four basic forms. The first form assumes that participants implicitly represent *abstract rules* that govern an environmental regularity, for example in the form of production rules (e.g., Figure 3). The second approach assumes that participants form representations with *fragments* of the learned materials (e.g., bigrams or trigrams from the left column in Appendix 1). The third interpretation assumes that participants learn *full instances* (e.g., letter-strings from the left column in Appendix 1). Finally, the fourth interpretation assumes that participants learn the statistical patterns associating elements of the regularity (e.g., transitional probabilities of letters in Figure 3). Currently, there is some agreement in that these characteristics do not necessarily constitute definitional properties of implicit knowledge; rather, they are taken as empirical inferences about the contents of the representations on which implicit processes operate.

2.1.3 The retrieval of implicit knowledge

How is implicit knowledge accessed? The retrieval of implicit knowledge has been conceptualized according to at least two major characteristics. The first characteristic is that memory access may be unintentional (e.g., Gabrieli, 1998). For example, in tasks in which participants are instructed to complete a word stem with the first word that comes to mind. In this case, the gains in reaction times or accuracy when participants are presented the same materials already learned are normally referred to as *repetition priming*, or simply, priming. In this context, repetition priming theoretically constitutes an index of implicit memory because previous experiences facilitate performance on the task without necessarily involving a conscious effort to remember the correct answer.

The second characteristic to conceptualize the access of implicit knowledge is in terms of adaptive behaviors that are not accompanied by conscious recollection or metacognitive awareness about the learning episode. For example, in some tasks participants are instructed to provide a recognition judgment and a metacognitive rating. Participants are asked whether the recognition decision itself is accompanied either by just a "feeling of knowledge" or by certainty about having studied the item before. The remember/know paradigm (Gardiner and Richardson-Klavehn, 2000) or the use of confidence ratings to supplement recognition judgments (Dienes and Scott, 2005) reflect this way of conceptualizing implicit knowledge.

Figure 1 summarizes the various aspects of implicit knowledge, starting from ordinary language to the more nested characteristics within each processing stage described in previous the paragraphs.

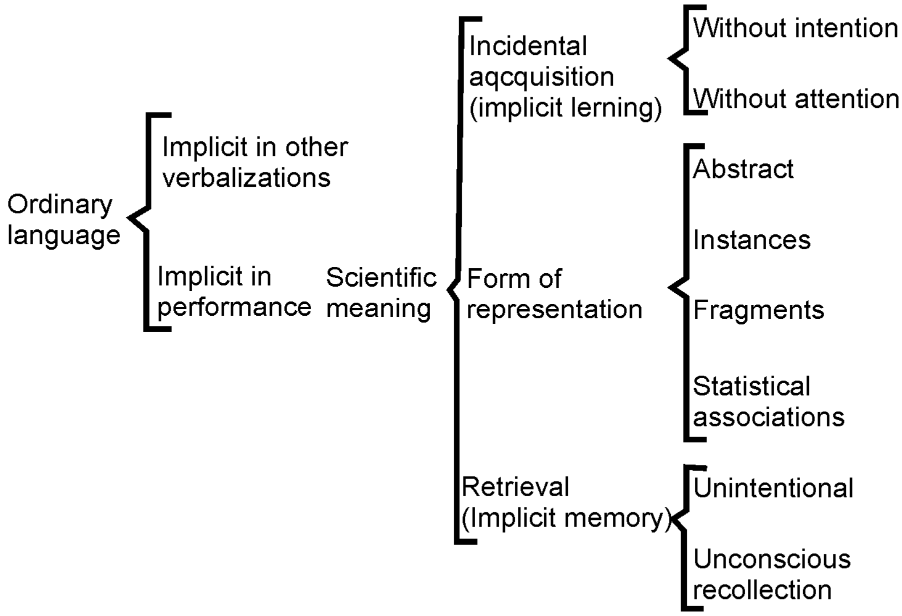

Figure 1: Synopsis of the various characteristics attributed to implicit knowledge starting with ordinary language meaning to the characteristics attributed within every processing stage (see text for more details and examples).

In this dissertation, I use the term implicit knowledge to reflect two characteristics, knowledge that is (1) acquired *and* (2) retrieved without intention. The first characteristic largely reflects the work on implicit learning whereas the second characteristic largely reflects notions of implicit memory. I endorse this definition because it provides many advantages if compared with other definitions. First, it links together research on implicit learning and research on implicit memory. Second, the definition does not require a compromise with notions that emphasize the form of representation. And, third, it derives in a clear-cut conceptual operationalization. On the one hand, operationalizations of implicit learning normally pursue a scheme in which participants are (a) exposed to some environmental regularity, (b) assessed with some performance test, and (c) measured on how conscious they are of the acquired knowledge. For example, the artificial grammar paradigm (Reber, 1967), the serial reaction time task (Nissen and Bullemer, 1987), and the dynamic system control task (Berry and Broadbent, 1984), are among the most commonly used paradigms that follow this operationalization pattern. A common feature of these paradigms is that participants are not informed about the environmental regularity which they are exposed to. In fact, the experiments I present in the empirical section of this dissertation adjust to this operationalization scheme common to most implicit learning tasks. Participants are neither informed nor instructed to search for any environmental regularity during the learning phase. In particular, participants are exposed to strings generated by artificial grammars (Experiments 1, 2, and 3) or to sequenced stimuli (SRT task Experiment 4A and 4B). The use I make of artificial grammars is, however, somewhat different than in the classic studies (e.g., Reber, 1967) because it emphasizes unintentional learning. In this case, participants are not required to memorize strings but rather are required to press the keyboard keys corresponding to a letter presented on the screen. In a way, this use of artificial-grammar tasks resembles a classic SRT task but instantiated with a pattern governed by an artificial grammar.

On the other hand, operationalizations of implicit memory follow a slightly different scheme: (a) requiring participants to *intentionally* memorize some information, (b) assessing their knowledge with implicit (indirect) tests, and (c) assessing their knowledge with explicit (direct) tests. The emphasis is therefore on comparisons between different *retrieval* conditions. It is assumed that one test primarily taps implicit knowledge whereas the other test primarily taps explicit knowledge. The word stem completion (Graf, et al., 1982), word identification (Jacoby and Dallas, 1981), and lexical decision tasks (Duchek and Neely, 1989; Rajaram and Roediger, 1993) are among the most studied paradigms in implicit memory research (Schacter, et al., 1993). A common feature of these paradigms is that participants are not required to recollect or remember the learning episode. They are only instructed to respond as rapidly and/or accurately as possible. In fact, the experiments reported in the empirical section of this dissertation conform also to this critical feature of research on implicit memory. Participants' knowledge is assessed with two different tests: one being primarily implicit and the other being primarily explicit. More specifically, recognition is considered a measure that primarily taps explicit knowledge, whereas reaction time priming is regarded as a measure that primarily taps implicit knowledge. However, the experimental paradigms employed here add to traditional implicit memory research the condition of not requiring participants to intentionally memorize the environmental regularity.

To recapitulate, the experiments I shall present share features with experimental paradigms used in both implicit learning and implicit memory research. In the learning phase, participants are not required to discover or generate explicit rules or knowledge about the environmental regularities. In the testing phase, participants' knowledge is assessed with both implicit and explicit tests. In the implicit tests, participants' knowledge is revealed by a facilitation effect (priming). As shown above, this definition of implicit knowledge conforms to currently accepted definitions for both implicit memory and implicit learning. It is stringent enough to rule out some characteristics of knowledge representation but is broad enough to include research on implicit memory and implicit learning.

This approach is remarkably similar to a division first held by Ebbinghaus (1885: /1992) between voluntary, involuntary and unconscious remembering. From Ebbinghaus' point of view, the distinctive feature of *voluntary* memory is that one can freely attempt to call back previously experienced states or perceptions to consciousness. In the case of *involuntary* memory, the states or perceptions are spontaneously recovered without any act of the will. The hallmark of *unconscious* remembering is that memories are indirectly revealed by facilitating processing of similar previous experiences. Note that in the characterization of implicit knowledge I portrayed above, the information is unintentionally acquired and unintentionally retrieved. Thus, it fulfills both the involuntary and unconscious remembering conditions of Ebbinghaus (see also Perlman and Tzelgov, 2006; Richardson-Klavehn and Bjork, 1988; Richardson-Klavehn, et al., 1996).

2.2 Dissociations

In this section, I deal with the issues of (1) whether dissociations between implicit and explicit tasks necessarily stem from independent implicit and explicit systems, and (2) how a graded perspective may help to understand potentially different patterns of forgetting. In fact, dissociations have become a crucial method to study implicit knowledge and skills. They have also been used for research in a number of other research areas such as category learning (Ashby and Spiering, 2004), decision making (Kahneman, 2003), or reasoning (Sloman, 1996). The typical finding in implicit learning and memory research is that when knowledge is measured with implicit tests, the participants usually score better than when knowledge is measured with explicit tests. This form of a single dissociation constitutes the essential and most widespread evidence for suggesting a separate implicit cognitive system or process (e.g. Schacter, et al., 1993). More precisely, the argument used in combination with evidence of simple dissociations attempts to bridge the gap between performance on implicit and explicit tests. The underlying logic for the use of dissociations may be summarized as follows: If (1) participants are exposed to an environmental regularity that supplies the learning system with information, and (2) participants perform better on an implicit test than on an explicit test, for which knowledge about the learned regularity is required, then (3) the existence of some additional process, system, or subsystem is assumed, which at some point in time, either *encodes* information in a different way or operates differently when the information has to be *retrieved.* For example, in his classic study, Reber (1967) showed that after requiring participants to memorize a set of strings generated by an artificial grammar, participants' discrimination performance of new grammatical and ungrammatical strings (implicit test) was better than their corresponding ability to verbally describe the knowledge on which they based their judgments (explicit test). Therefore, Reber concluded that some other system should operate outside the scope of awareness in order to enable the adaptive performance on the discrimination task.

However, the inference logic implied in single dissociations has been heavily criticized because it makes use of two assumptions that are presumably difficult to meet, the *selective influence* assumption and the *equal sensitivity* assumption (Dunn and Kirsner, 1988). The former assumption states, in its simpler form, that each assumed underlying process must contribute to only one task if a single process explanation for the dissociation is to be refused. This assumption has generated an interesting body of research that is based on the idea that there is a possible "contamination" of implicit knowledge on explicit tests or conversely, contamination of explicit knowledge on implicit tests (e.g., Jiménez, et al., 1996; Watkins and Gibson, 1988). This discussion revealed the crucial role some other factors such as *fluency* may have on dissociations (Buchner, et al., 1997; Kinder, et al., 2003) and made clear the need of additional formal criteria to consider dissociations a valid index for the operation of multiple systems.

The latter assumption is that the dissociation must not be due to a difference in *sensitivity* between implicit and explicit tests. Criticisms based on the issue of sensitivity have also generated empirical research to provide an account for dissociations in terms of a single knowledge-base system with different sensitivities for the implicit and explicit tests.

To deal with this difficult issues, many methodological strategies have been proposed both in implicit memory and implicit learning research: (1) to equate implicit and explicit tests in all relevant aspects except instructions (Meulemans and Van der Linden, 1997; Reingold and Merikle, 1988), (2) to use the opposition logic to estimate the contribution of controlled and uncontrolled influences on explicit measures (Jacoby, 1991), (3) to combine the opposition logic with the identification of additional factors such as recollection, fluency, systematicity detection, and guessing (Buchner, et al., 1997), and (4) to use subjective tests of awareness (Dienes, 2004; Kunimoto, et al., 2001). Critical to all these alternatives is an attempt to obtain a clean measure of explicit knowledge that is unaffected by implicit knowledge.

In this regard, a highly influential view in learning research has been proposed by Shanks and St. John (1994). They suggested that dissociations between measures of implicit and explicit learning should satisfy three criteria in order to be considered valid indices of the operation of an alternative underlying system. These are, (a) the information criterion, (b) the sensitivity criterion, and the less explicitly formulated, (c) concurrency criterion. The information criterion requires that awareness tests tap the knowledge that is needed to support performance on the corresponding implicit test. For instance, successful classification in an artificial-grammar-learning task is not necessarily based on knowledge of the rules of the grammar; instead it may involve knowledge about specific similarities between training and test items. Participants asked about the rules of the grammar would then understandably fail to offer relevant explicit knowledge. The work of Dulany, Carlson, and Dewey (1984), for instance, clearly showed that probing participants not about their general rule knowledge but simply about their ability to identify which letters made a string grammatical was a much more sensitive way of revealing the subjects' conscious knowledge.

The sensitivity criterion requires that awareness tests should be sensitive to all conscious knowledge. It is possible that some conscious knowledge is affecting implicit performance but this conscious knowledge is not detected by the explicit test because it is not sensitive enough. For example, it is possible that asking participants to verbally describe their explicit knowledge about a sequence is simply a more difficult task than making them to respond with a key press.

The concurrency criterion is closely related to the sensitivity criterion. It requires that both the explicit and the implicit tests are elicited as concurrently as possible. Accordingly, the finding that an explicit test fails to be sensitive to the relevant information does not necessarily imply that the information was processed unconsciously during encoding, but that, for instance, it might have been forgotten or distorted before retrieval.

According to these criteria, implicit knowledge is demonstrated when conscious knowledge equals zero and, simultaneously, implicit knowledge is above zero. However, a radically different perspective was originally proposed by Reber who suggested that it would be enough to show that implicit knowledge is greater than explicit knowledge in order to infer the operation of an additional implicit learning system. One of the reasons for these different views is that the full set of criteria proposed by Shanks and St. John has proved to be very difficult to satisfy in a single study (but see Reber, 1998). For example, it is not possible to simply “shut down” participants’ conscious processing in order to observe if some knowledge is acquired in its absence (Cleeremans, 1997). For this reason, in this dissertation I take a new perspective. The question here is not whether learning may ultimately proceed without awareness or whether knowledge is unintentionally retrieved in the absolute. The key question concerns whether the repetition of the same measures after a retention interval displays a different pattern of forgetting. This graded perspective may solve many problems. First, because implicit and explicit measures are exactly repeated after a retention interval, it is probable that changes detected in the level of information do not crucially depend on the measures’ sensitivity, because there is no reason to assume that sensitivity changes with time. A second advantage is that it is not necessary to prove that conscious knowledge is completely absent but simply that it changes with time. Third, I maximize the comparability of the implicit and explicit tests by eliciting explicit recognition judgments after every measurement of implicit knowledge.

In Figure 2, I illustrate one of the simplest ways in which a graded perspective may help to understand dissociations between implicit and explicit tests from a single-system perspective. In this figure, I1 to I5 represent different critical intervals of time determined by the intersection of various grades knowledge strength with two hypothetical implicit and explicit thresholds. Consider that (1) knowledge strength may increase during learning and may decrease during a retention interval, and (2) that the threshold to detect implicit knowledge is lower than the threshold to detect explicit knowledge. If tests were conducted before any training, for example during the first interval (I1) then both measures should not detect any knowledge. The same pattern of findings should be observed after a considerable retention interval (I5) due to forgetting. More interestingly, during I3 both implicit and explicit measures are able to detect knowledge due to the fact that information is strong enough to be reliably measured by both implicit and explicit tests. However, dissociations may be observed at I2 and I4 intervals and may be accounted for from a single-system perspective assuming a unitary knowledge base. On the one hand, observations at I2 would correspond to most findings in implicit learning literature reporting evidence of implicit knowledge in the absence of explicit knowledge; this dissociation might be accounted for by arguing that explicit tests are more difficult or less reliable. On the other hand, a transition from I3 to I4 might account for evidence of dissociations in implicit memory research reporting impaired performance on the explicit task but spared performance on the implicit task. In other words, dissociations between implicit and explicit tests in learning and memory research may be explained as the product of different thresholds without assuming that implicit and explicit knowledge are qualitative different (i.e., note that there is only one single line representing knowledge in Figure 2).

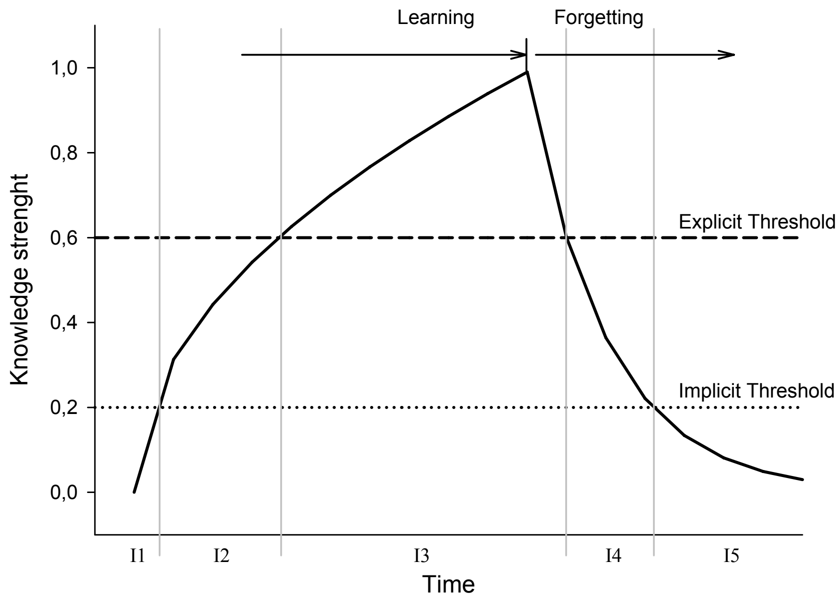

Figure 2: Hypothetical learning (knowledge increases from near 0 to near 1) and forgetting (knowledge decreases from near 1 to near 0) for a single-system model assuming a graded perspective of knowledge strength. The dotted line represents a threshold for implicit knowledge whereas the dashed line represents a threshold for explicit knowledge. Vertical lines illustrate critical testing times according to the magnitude of knowledge and its intersection with the thresholds. I1, I2, I3, I4, and I5 depict intervals of time when different correlations and dissociations between measures are hypothesized.

However, as explained before, there is no guarantee that tasks depict clear-cut differences in the knowledge base. In the case of some explicit tasks such as recognition judgments, it is possible, for example, that fluency or guessing affects performance independently of knowledge strength (e.g., Buchner, et al., 1997). To deal with this issue, in the experiments described in the empirical section of this dissertation, I complemented recognition judgments with confidence ratings about the recognition decisions. This strategy may be better justified within a metacognitive theoretical framework that includes the use of *subjective measures* such as confidence ratings. Below, I explain this approach in detail.

The use of confidence ratings has been justified by appealing to the notions of subjective and objective thresholds (Cheesman and Merikle, 1984). The central assumption is that performance on a given task (e.g., recognition) is thought to be below the subjective threshold if performance is better than chance while participants indicate that they are guessing (e.g., through confidence judgments). Performance is thought to be below the objective threshold if it does not differ from chance.

According to this logic, implicit knowledge would be demonstrated whenever performance is below the subjective threshold and above the objective threshold. Dienes, Altmann, Kwan, and Goode (1995) operationalized this logic by proposing two criteria to assess the extent to which knowledge is implicit. The first criterion is the *guessing criterion*, which states that one can conclude that knowledge is implicit to the extent that people perform better than chance while believing that they are guessing. The second is the *zero-correlation criterion*, which states that one can conclude that knowledge is implicit if confidence judgments fail to correlate with participants' performance on implicit tests. Some experiments have successfully applied these ideas in the domains of artificial grammar learning (e.g., Dienes and Altmann, 1997) and sequence learning (e.g., Shanks and Johnstone, 1998).

However, there are clear methodological limitations involved in the use of subjective measures of conscious awareness (Reingold and Merikle, 1990). For instance, people might simply refrain from reporting knowledge held with low confidence or might offer reports that are essentially reconstructive (Nisbett and Wilson, 1977). For this reason, many authors have advocated the use of *objective measures* of awareness. These measures include binary recognition judgments such as the one employed in the empirical part of this dissertation. Additionally, in order to control for the possibility of contamination from implicit knowledge, I make use of confidence ratings associated with every recognition judgment.

To summarize, taken together all criteria, in the present dissertation I use a strategy composed of three different kinds of tests: implicit tests based on reaction time (objective measure), explicit tests based on recognition (considered an objective measure), and confidence ratings for every recognition test (considered a subjective measure). Additionally, all three tests are repeated after a retention interval, this latter perspective drawing significantly on the idea that knowledge strength ought to gradually change with the passage of time.

2.3 Distinguishing between systems

Merely talking about multiple or single memory systems involves a simplification of many fine grained views and approaches. In this section, I revisit the conceptual work carried out to abstractly distinguish the notion *system* from related concepts such as process, subsystem, or forms of learning and memory. Then, I attempt to identify the criteria used to postulate an independent learning or memory system. Finally, I present details on existing multiple-system and single-system theories in implicit learning and implicit memory.

Some previous attempts have been made to distinguish between the concept of "system" and related concepts such as "processes", "forms of memory", "tasks", and "subsystems", which are sometimes misleadingly used in the literature (Schacter and Tulving, 1994). It has been proposed that talking about *forms* of memory or learning is simply less stringent than talking about a memory system or a learning system. For example, Schacter (1994) has suggested that different forms of learning and memory do not need to be associated with different systems, e.g., olfactory memory, recognition memory, concept learning, rule learning, etc. These concepts are intended to be simple descriptions and are not intended to constitute memory or learning systems per se.

Another common practice identified by Schacter and Tulving (1994) is to talk about memory or learning *processes* (e.g., Barrett, et al., 2004; Yonelinas, 1994). In this case, authors indicate a specific operation executed to support memory or learning performance. For example, identification, attention, activation, etc. These processes may support different or similar systems but are not necessarily considered identical with them. For example, the same process may participate in the operation of more than one memory system (e.g., Roediger, 1990).

Schacter and Tulving (1994a) also noted that an important relation exists between tasks and systems. According to these authors, *tasks* may constitute behavioral (including verbal) expressions of a system. They are normally viewed as tests that tap some system to a greater degree than others but may not be equated with the operation of a single system. Therefore, many researchers have suggested that inferences about different systems should be based on converging evidence from a variety of tasks and should not depend solely on results from a single task (e.g., Johnson and Hasher, 1987). It has been suggested that probably the best way to characterize the relations between tasks and systems is in the form of many-to-many, in the sense that many systems may support performance on a task (Squire, et al., 1993).

Finally, a conceptual boundary has also been drawn between systems and *subsystems*. It has been suggested that subsystems process different kinds of information but share the principal rules of operations of their superordinate system. For example, in Baddeley's framework for working memory (e.g., Baddeley, 1998), the visual and verbal subsystems basically follow the same operational rules but each subsystem processes information in different formats.

Until now, I have presented a terminological clarification between related concepts that are sometimes misleadingly equated with systems such as forms, processes, tasks, and subsystems. What are the criteria needed in order to argue that different memory systems underlay performance? Ashby and Ell (2002) analyzed this question in detail and suggested a set of useful steps to clarify this issue. Similarly, Schacter and Tulving (1994) proposed a series of conditions to define different memory systems. Taken together, these authors suggest that independent learning or memory systems should differ according to the following criteria:

1. The systems should provide different adaptive functions.
2. The systems should operate according to different laws or properties.
3. The systems should be implemented in separate neural substrates.
4. The systems should have different phylogenetic and ontogenetic developments.
5. The systems should differ in the form they represent information.
6. The systems should have different patterns of temporal retention and forgetting of information.

Should all these criteria be satisfied for 2 systems to differ? Currently, there is no agreement about this issue, but the general strategy has been to accumulate empirical evidence in favor and against the multiple systems view for each of these criteria. In Chapter 3, I will present a summary of this empirical evidence for each criterion. However, I explain first the theoretical basis of existing multiple-system and single-system theories in implicit memory and implicit learning.

2.3.1 Multiple-systems view in implicit memory

The idea that memory and learning consist of multiple elements that are not of the same kind has been recurrent in philosophy and psychology. For example, Aristotle differentiated between remembering and recollection. For him, remembering implies awareness about the contents of the events recovered, a sort of reviving of previous experiences; while recollection is a manner of accessing past knowledge (*reminiscentia*) fundamentally reconstructive and associative (Sorabji, 2004).

Schacter and Tulving (1994) conducted a historical survey on the idea of multiple forms of memory in order to identify the theoretical basis of the multiple-system view. According to them, Maine de Biran (1776-1824) was the first who clearly postulated a framework for separate kinds of memory. The cornerstone of this framework lies in the difference between mechanical, sensitive, and representative forms of memory. Mechanical memory presumably operates unconsciously and involves the acquisition of motor and verbal habits. Sensitive (or sensory) memory is involved in acquiring feelings, affects, and brief (ephemeral) images. Representative memory is involved in conscious recollection of ideas and events. From Biran's point of view, the first two forms of memory operate largely outside the scope of awareness. Accordingly, mechanical and representative memory systems serve very distinct functions and can be exercised without the other. Both mechanical and sensitive memories operate without representations and largely outside the scope of volition. The main difference between them is that mechanical memory is involved in motor learning, whereas sensitive memory operates in the affective domain.

Other important contributions to the idea of multiple-memory systems arose from early work on psychophysiology. For example, Paul Broca (1824-1880) argued that patients' deficits in declarative memory (inability to generate language output) reflect damage to a particular kind of memory, not in memory involved in words' meaning but in memory of the procedure required for articulating words.   For Broca, this special kind of memory was neither related to other kinds of memories nor to intelligence (see Rosenfield, 1980).

Likewise, Carl Wernicke (1848-1905) made observations on aphasia, on which patients had no difficulty producing linguistic output but had severe comprehension problems. He interpreted these symptoms in terms of damage to a special memory center for auditory word representations; this center was apparently distinct from the memory damaged in Broca's case .

Another key foundation is the work of Scoville and Milner (1957) who studied the role of the medial temporal lobe, including the hippocampus in patient H.M. who had undergone a complete bilateral resection of the medial temporal lobes. This patient showed impairment of his ability to remember recent experiences and acquire new knowledge. However, his overall intelligence remained above average as well as other cognitive and perceptual functions. Warrington and Weiskrantz

(1968, 1974) showed later that amnesic patients retained their relative ability to perform fragment-cued tests of previously encountered verbal and pictorial material, despite their diminished ability to recognize these materials as previously encountered.

In 1994, a book edited by Schacter and Tulving compiled the main contemporary approaches to the multiple-systems perspectives on memory. Based on the contributions to the volume, Schacter and Tulving identified five major memory systems: procedural memory, perceptual representation memory, semantic memory, working memory, and episodic memory. Retrieval in the first three memory systems is presumably implicit whereas retrieval in the latter two is explicit.

Recently, Squire (2004) has presented a review on the multiple systems perspective. This review attempts to demonstrate that most empirical findings can still be embraced by a nested taxonomy whose starting division distinguishes between implicit (nondeclarative/procedural) memory and explicit (declarative) memory. I take his review as the standard and most updated approach to multiple-memory systems.

The starting point of the multiple-memory systems approach is to recognize that the term *implicit memory* is a descriptive concept. It was originally intended to characterize a different form of memory “revealed when performance in a task is facilitated in the absence of conscious recollection” (Graf and Schacter, 1985: p. 501) as opposed to memory whose content is conscious or whose retrieval strategy is intentional. Currently, the taxonomy proposed by Squire distinguishes, first, between declarative (explicit) and nonedeclarative (implicit) memory. Declarative memory is further divided into semantic memory (facts about the world) and episodic memory (reexperiencing the learning episode). On the other hand, nondeclarative memory comprises procedural skills, priming and perceptual learning, classical conditioning, and nonassociative learning. One distinctive feature that groups together all nondeclarative memory (implicit) subsystems is that they are supposed to gradually extract information about common elements of the environment. This information is characterized as dispositional knowledge expressed through performance. It is additionally argued that different memory systems operate in parallel; consequently, a learning situation can lead to a stable declarative memory for the event itself as well as a long lasting nondeclarative behavioral adaptation (Squire, 2004).

Two different subsystems have been proposed to account for nondeclarative behavioral adaptations (Schacter, 1987; Schacter, 1990; Schacter and Tulving, 1994; Schacter, et al., 2000). One of them is basically *perceptual* and is supposed to account for priming and perceptual learning. The other subsystem is eminently *procedural* and is intended to account for skills and motor performance.

The perceptual representation system (PRS) is assumed to process and represent information about the form and structure of the environment, but not the meaning and other associative properties of words and objects. It processes, for example, the visual form of words, their acoustic properties, and other similar perceptual and structural characteristics of the environment (Schacter and Tulving, 1994). Repetition priming purportedly reflects the operation of this system (Schacter, 1994). Additionally, the PRS is assumed to be composed of three subsystems: (1) the visual-word-form system (cf. Price and Devlin, 2003), (2) the auditory-word-form system, and (3) the structural description system (cf. Marsolek and Burgund, 2005). Schacter also proposed that the output of the PRS subsystem can serve as input to episodic memory; this is so because one key function of the episodic system is to bind perceptual with other kinds of information (semantic, contextual, etc.) and thereby allow subsequent recall or recognition.

On the other hand, the procedural memory system is supposed to store information about motor and cognitive skills, which are necessary to respond adequately to properties shared by similar environmental situations. Although Schacter (Schacter, et al., 2000) has proposed that the procedural memory system likely includes major subdivisions that have not yet been further specified (cf. Fernandez-Ruiz and Diaz, 1999).

2.3.2 Multiple-systems view in implicit learning

There are many versions of multiple-learning systems that do not necessarily compete against each other but rather constitute refinements of previous accounts. The common denominator among them is the assumption that different forms of knowledge may be acquired through functionally different processes. However, they differ in the scope and specificity of cognitive phenomena explained by different theories. The "first generation" of multiple-learning systems comprises broad descriptive cognitive theories stressing the character of implicit learning as a form of default process occurring outside the scope of awareness (Reber, 1967; Reber, 1969;

Reber, 1993; Reber and Allen, 1978). A "second generation" of multiple-system versions constitute recent developments circumscribed to the acquisition of motor performance and non verbalizable forms knowledge (Keele, et al., 2003; Willingham, 1998). A "third generation" of theories highlight the complementary interaction between implicit and explicit processes (McClelland, et al., 1995; Sun, et al., 2005). In this section, I provide details on these 3 different generations of theories of multiple learning systems.

The first suggestion of implicit learning, portrayed by the pioneer work of Arthur Reber and his co-workers, has 2 pivotal assumptions. First, the so called "implicit stance", this is, the premise that implicit learning is general and universal, and that implicit acquisition is the default mode adopted by learners. Second, the generic assumption that implicit learning processes produce abstract representations of the environment.

Reber's central ideas evolved into computational and neuropychological theories of implicit learning devised to account for the acquisition of prototypical forms of implicit knowledge such as skill learning and procedural knowledge. The control-based learning theory of Daniel Willingham (1998), went one step further in hypothesizing specific processes that may be involved in implicit and explicit learning of motor skills. Willingham (1998) proposed that motor skills are in fact learned through three different implicit processes and one explicit process. The implicit processes consist in (1) selecting special targets for movement, (2) sequencing these targets, and (3) transforming them into muscle commands. All these three processes are assumed to operate outside the scope of awareness. A fourth conscious process, improves performance by strategically selecting more effective goals or by selecting and chunking spatial targets. Similarly, Keele et. al. (2003) adopted a multiple-system perspective by suggesting that two different systems are involved in motor sequence learning. These systems are assumed to be based on different neural pathways, different attentional requirements, and different forms of representing sequential knowledge. One system processes information from multiple dimensions whereas the other system is unidimensional. Consequently, the systems differ in terms of (1) their dimensional codes, and (2) their computational capability. It is assumed that the multidimensional system builds associations and integration between events from different dimensions or modalities. Therefore, this model suggests that the multidimensional system enhances contextual learning and facilitates learning of relatively complex sequences and categorized stimuli. The task set determines which signals or dimensions are relevant for the multidimensional system. For example, from the perspective of this model, a secondary task interferes with cross-dimensional learning not because it limits the resources or because it causes distraction, but because it disrupts coherence between successive events.

On the other hand, the unidimensional system associates relatively simple uninterpreted stimuli. This factor makes the system relatively robust to potentially disruptive information from other dimensions. The formation of associations in this system is assumed to occur in encapsulated modules, even when information along other dimensions may be relevant for the task at hand. Learning in this unidimensional subsystem is hypothesized to be entirely implicit.

The distinction between multidimensional and unidimensional systems suggests that the first system may confer the possibility of transfer to new modes of expression, which is the basis of awareness but, according to the authors, this assumption does not imply that, by default, the multidimentional system operates consciously. On the other hand, it is assumed that the unidimensional system, necessarily produces representations not available to awareness, because it operates in close encapsulated modules.

McClelland, McNaughton and O'Reilly (1995), also proposed an integrative theory of implicit and explicit learning and memory. Their core idea is that there are two complementary learning systems. One in the hippocampus and other in the neocortex. The hippocampal system (see also Eichenbaum, 1994; Eichenbaum, 2000; see also Nadel, 1994) is responsible for rapid learning of arbitrary associations assumed to provide the basis for explicit recall of specific episodes. The neocortical system is involved in gradually processing and accumulating information of similar events required to perform cognitive skills. There is an intimate bidirectional communication between these two systems. The hippocampal system stores "compressed" information about associations between environmental regularities and responses after extensive successful performance. When the hippocapal representations are required, they are not directly expressed in performance but are first transferred and reinstated in the neocortical system. Thus, the information needed to reconstruct a particular pattern of activation is not directly stored in the hippocampal system.

2.3.3 Single-system views in implicit memory

Most modern theories of memory involve in a way or another the assumption that diverse structural or procedural subdivisions are required to perform different memory tasks. However, one important account of implicit memory holds, that the postulation of multiple memory systems is neither necessary nor justified and that relevant dissociations can be understood in terms of relations between processing operations carried out during study and tests (Blaxton, 1989; Roediger, et al., 1989).

More specifically, this theory has 4 basic assumptions. First, memory tests may benefit from the fact that the cognitive operations they require overlap or recapitulate the operations used during encoding. Second, it is assumed that implicit and explicit tests rely on different types of processing. Third, explicit tests are assumed to depend on meaningful information for their successful performance. Fourth, implicit tests are assumed to rely on perceptual information. Consequently, these assumptions predict that performance on most implicit tests should benefit from a study phase that provides appropriate (perceptual or motor) practice for the later test because the type of processing is one crucial determinant of the dissociation.

However, some problems have been noted in this approach. For example, there is no clear boundary between perceptual and conceptual levels of analysis. Rather, some perceptual experiences may give rise to meaning because they may depend on classifying objects into abstract categories. In fact, later formulations of this "processing" account have acknowledged that the debate on multiple memory systems is often mistakenly framed as being between proponents of unitary versus proponents of multiple memory systems. Apparently, the current processing view endorsed by Roediger and collaborators does not necessarily suggest that memory is "unitary" or monolithic. Instead, this account emphasizes that performance on memory tests may be dissociated because there are different *processes* required to perform the specific tasks involved in the tests. This suggest that the "processing" view may contrast more sharply with abstractionist theories (e.g., Anderson, 1990) than with multiple-system perspectives. More recently, the transfer-appropriate processing framework, originally intended a an alternative to memory systems, have moved closer to the multiple systems perspective in recognizing that the original framing of the questions in terms of systems and processes was too simplified.

Currently, there seems to be agreement in that theories postulating memory systems and theories postulating a processing viewpoint have moved closer together. These two views provide complementary rather than competing perspectives. For example, newer versions of the procedural view emphasize that the neurocognitive systems are complex and interactive, Moscovitch (1994) proposed, for instance, an interactive view in which any task can be seen as a more or less complex concatenation of component processes susceptible of both structural and procedural characterizations.

2.3.4 Single-system views in implicit learning

A number of different single-systems perspectives on learning have been proposed in the literature. In the first part of this section, I attempt to introduce their common theoretical basis and assumptions. In the second part, I focus particularly on the version proposed by Shanks and collaborators.

The study of implicit learning evolved against a background in which research on explicit, deliberative cognition was dominant. Before the emergence of implicit cognition as a topic in cognitive psychology, most research focused on the study of explicit hypothesis-testing mechanisms (e.g., Millers' Project Grammarama; Bruner, Goodnow & Austin 1966). From its outset, the cognitive revolution emphasized the study of processes occurring within the "black box" which, purportedly, could not be accounted for from a purely stimulus-response (associative) standpoint. It was thought that consciousness was required in most complex human cognitive actions such as decision making, abstraction, planning, reflection, and creativity (Velmans, 1991). Understandably, the postulation of alternative implicit system(s) or mechanisms was regarded as highly innovative in this context.

However, most single-system perspectives depart from the above mentioned standpoint in at least one of the following two fundamental ways. Those influenced by an associative tradition argue that it is not necessary to distinguish between implicit and explicit processing, mainly because from this point of view unconscious processes are not considered susceptible to scientific inquiry (Shanks, 2005). For different reasons, cognitively oriented psychologists with an emphasis on symbolic processing arrive at a similar conclusion; the study of implicit knowledge is regarded as paradoxical because simple associative processes (such as Pavlovian conditioning) are supposed to be relevant only to the extent that they reveal something about the underlying explicit cognitive system (Bargh and Ferguson, 2000; Furedy and Kristjansson, 1996). Indeed, it has been argued that this interplay appears to leave no room for a scientific construction of implicit cognition (see Cleeremans, 1997, for an overview).

In fact, a useful way to characterize different single-systems models, is to ask whether the model assumes that learning processes *invariably* produce conscious knowledge (Frensch and Runger, 2003). Some *restrictive* versions assume that all knowledge is generated by a single learning process. From this point of view, participants process information by following automatic associative principles (e.g., Perruchet, et al., 1997; Perruchet and Vinter, 2002). Accordingly, awareness about the contents of learning processes emerges mechanically as a by-product of adaptive behavior (e.g., Perruchet and Vinter, 2003).

A second, *permissive*, version also assumes the existence of a single-learning system but allows for the possibility that the system generates both implicit knowledge expressed in the form of adaptive behavior without awareness and explicit knowledge in the form of verbalizations or recognition. For example, the work of Whittlesea and collaborators (e.g., Leboe and Whittlesea, 2002; e.g., Whittlesea and Dorken, 1997), assumes that all markers of knowledge are basically implicit and that explicit knowledge is generated by applying inference heuristics such as fluency. It is argued that participants can detect the relative ease of perception of an item and can use the fluent perception of old items as part of the basis for (explicit) recognition judgments.

In turn, there are two slightly different forms of permissive single-system models depending on whether the emphasis is on (1) internal cognitive processes involved in the translation from the memory trace to the observable performance or on (2) external properties of the tasks (i.e., the test's measurement error). The first view tends to emphasize that dissociations are due to different *translation* process from the memory trace to the overt behavior. For example, Humphreys (1989) distinguished between modality-specific and modality-independent memory codes. He suggested a single memory system in which memories are represented in distributed networks but are accessed via two fundamentally different cognitive operations: matching and retrieval. The matching operation is the comparison between the cue and the memory trace, while the retrieval operation is the translation from the memory trace to overt performance.

The second view, emphasizes that dissociations are the product of different *sensitivities* of the implicit and the explicit tests. For example Zaki et al. (2003) studied whether dissociations between categorization (implicit task) and recognition (explicit task) performance in amnesic patients may simply be due to differences in the difficulty of the tasks. They tested amnesic participants in a difficult categorization task by using two categories and including presentations of the old training category. Under such conditions, it was found that the impairment of performance on the explicit recognition task was similar to the impairment of performance on the implicit categorization task. These findings were taken to support the idea that categorization and recognition depend on the same representations.

In fact, a key assumption of this later "subfamily" of single-system models is that both forms of knowledge are based on the same memory trace but they are differentially expressed in task performance due to different error measurements involved in explicit and explicit tests (e.g., Kinder and Shanks, 2003; Shanks, et al., 2003; Wilkinson and Shanks, 2004). This version of single-system model has gained importance because it has been argued to be more parsimonious than most dual-system versions. At the same time, it has been used to account for dissociations reported with amnesic patients (Kinder and Shanks, 2001; Kinder and Shanks, 2003), learning of sequences (Shanks and Perruchet, 2002; Shanks, et al., 2003), and memory phenomena such as repetition priming and recognition (Berry, et al., 2006). For example, Kinder and Shanks (2001) simulated dissociations between classification and recognition of amnesic patients with a single (non modular) connectionist network. In this version of the network, dissociations were produced by assuming that normal participants learn faster than amnesic patients. Similarly, Berry et al (2006) simulated dissociations in memory performance between priming and recognition tasks. These authors assumed that (a) a single memory strength variable supports performance in priming and recognition tasks, and (b) that the noise associated with decisions in the priming task is greater than that associated with the recognition task. This model predicts that recognition is more sensitive to the underlying strength variable than is priming. Therefore, the authors concluded that it is unlikely that priming will be found in the absence of recognition (or that the magnitude of priming will be greater than that of recognition, when compared within the same response metric).

This version of a single-system has also been turned into a computational model to account for dissociations between priming and recognition in SRT tasks. This model enables an estimate of implicit and explicit knowledge after a learning episode in which recognition may be dissociated from priming. Interestingly, in this realization of a single system, recognition is assumed to have lower reliability than priming. In the empirical section, I will present concrete details about the computational features and parameters of this model as well as simulations intended to evaluate and extend its ability to account for patterns of forgetting rates of implicit and explicit knowledge.

3 Empirical evidence of multiple systems

In Chapter 2, I identified 6 a priori criteria that may be used to justify the postulation of multiple memory and learning systems. I also sketched the theoretical foundations of both the single and the multiple-system perspectives in learning and memory research. In the present chapter, I attempt to weight the evidence for each of these criteria and to identify the open questions. I particularly elaborate on the 6th criterion, that is, evidence of different patterns of temporal retention for implicit and explicit knowledge.

In general, the evidence for multiple-memory systems is vast and complex (Butler and Berry, 2001; Graf and Masson, 1993; Lewandowsky, 1998; Lewandowsky, et al., 1989; Reder, 1996; Richardson-Klavehn, et al., 1996; Roediger, 1990; Schacter, 1987; Schacter, 1994; Schacter and Tulving, 1994; Schacter, et al., 2000). For example, implicit memory has not only been studied with normal healthy participants (Roediger and McDermott, 1993) but the initial impetus came also from research with amnesic patients. Hence, the debate about the existence of implicit memory systems includes also neuroscientific evidence (e.g., Gabrieli, 1998; Milner, et al., 1998). Another characteristic of the bulk of empirical evidence is that it reflects the use of different concepts of implicit memory. Persistently, implicit memory appears intimately linked, and many times merged, with slightly similar concepts such as procedural knowledge, nondeclarative memory, etc. Such terminological flexibility reflects, of course, different research interests but it has also made the discussion difficult to understand. Additionally, many methodological questions have constantly pervaded the discussion: the role of intention to remember, the role of awareness of the encoding episode, the difference between implicit memory as a form of testing and implicit memory as hypothetical construct, etc. The intricacies of implicit memory research are reflected in the fact that despite numerous attempts to comprehensively review the field (e.g., Bowers and Marsolek, 2003; Butler and Berry, 2001; Graf and Masson, 1993; Nyberg, 1996; Richardson-Klavehn, et al., 1996; Roediger, 2003; Roediger and McDermott, 1993; Schacter, et al., 1993; Schacter, et al., 2000; Squire, 2004; Tulving and Schacter, 1990; Underwood, 1996), no review has claimed to be exhaustive. Indeed, most reviewers have complained about the complexity, large amount of evidence, and the several empirical constrains that any theory of implicit memory should fulfill. In order to overcome these difficulties, I focus on the 6 criteria mentioned in the previous section. Sometimes, these criteria are not completely unambiguous but they do provide a way to organize and weigh the empirical evidence. Consequently, each forthcoming section is devoted to review empirical evidence for one of the following criteria:

1. The systems should provide different adaptive functions.
2. The systems should operate according to different laws or properties.
3. The systems should be implemented in separate neural substrates.
4. The systems should have different phylogenetic and ontogenetic developments.
5. The systems should differ in the form they represent information.
6. The systems should have different patterns of temporal retention and forgetting of information.

3.1 Functions of implicit and explicit systems

In evolutionary terms, it is considered that the broad function of the cognitive system is to optimize behavioral adaptations to the environment (e.g., Cosmides and Tooby, 1987). It is assumed that this optimization is constrained by a tradeoff between the need for timely and relevant responses on the one side, and the requirement to maximize cognitive resources on the other side. It follows from this perspective, that the assumed function of the implicit memory system is to provide adaptations to the environment that require few cognitive resources but slow accumulation of information. On the other hand, the assumed function of the explicit memory system is to provide more flexible and faster adaptations to the environment by monitoring performance and by directing attention to relevant environmental features but with the disadvantage of requiring a large amount of cognitive resources (e.g., Klein, et al., 2002; Reber, 1993).

In this regard, there is evidence that implicit knowledge is, in fact, gradually acquired, that it crucially relies on exploiting environmental regularities, and that it does not necessarily benefit from concomitant explicit knowledge about the environmental regularities (e.g., Heuer and Schmidtke, 1996; Karni, 1996; Kleinsorge, et al., 2003). Additionally, it has been shown that this form of knowledge may proceed relatively unaffected when attention is distracted from the main task (Frensch, et al., 1994; Frensch, et al., 1998; Heuer and Schmidtke, 1996).

However, it has also been shown that some minimal attentional resources may nevertheless be required to acquire this sort of information (Shanks and Channon, 2002; Shanks, et al., 2005).

It appears that the bulk of evidence confirms that implicit knowledge (in the form of perceptual or motor skills) increases gradually and requires fewer cognitive resources than explicit knowledge. In general, there seems to be agreement between proponents of both single and dual-system views in that the cognitive system is able to accomplish qualitatively different adaptive functions. However, as I will discuss in the next section, there is no agreement on whether different adaptive goals are fulfilled by following the same principles of operation.

3.2 Properties of operation

The main venue of evidence supporting the idea of different memory systems originates from research pointing to the fact that performance on implicit tests apparently follows different rules of operation than performance on explicit tests. This evidence relies primarily on *repetition priming*, that is, a facilitation of responding manifest in improved reaction time or accuracy to previously encountered stimuli[1]. Indeed, it has been extensively shown that this facilitation can be dissociated from explicit forms of memory such as recall and recognition. The assumed explanation for this sort of dissociation is that different forms of memory apparently operate according to different principles. For example, Jacoby and Dallas (1981) attempted a systematic comparison of priming performance on implicit and explicit tasks. These authors contrasted what they called autobiographical memory in the form of binary (yes-no) recognition judgments with perceptual recognition, that is, a task in which participants had to report words that were briefly flashed (35 ms). They manipulated the effects of various variables: level of processing, learning process (incidental versus intentional), retention interval, and perceptual familiarity. To study the depth of processing, for example, participants were required either to simply read the words or to attempt to complete anagrams. A notable observed dissociation was that difficulty and level of processing showed large effects on recognition (explicit) memory (as assessed by the yes-no recognition judgements)

[1] Despite the fact that some other domains of research such as conditioning, skill learning, or attention may qualify as implicit memory phenomena, there is some consensus that priming best reflects the search for different functions of the implicit memory system.

but no effect on perceptual recognition (implicit memory as asseded by reports of words briefly flashed), in agreement with the idea that the primary function of implicit memory is to store perceptual information. However, other variables showed high correlations. For example, a brief study presentation was enough to similarly influence perceptual reports and recognition judgments even after a 24 hr. retention interval. It was also found that a change in the modality from the learning to the testing phases (auditory-visual or visual-auditory) reduces both perceptual and recognition memory performances.

In the early 80s, several publications addressed similar issues. Attempts to critically review the existing literature to date (Richardson-Klavehn and Bjork, 1988; Schacter, 1987) agreed in that for normal participants, implicit memory tests behave according to different rules or principles than explicit memory tests in the face of (1) encoding manipulations (e.g., requiring participants to encode words either semantically or orthographically), (2) elaborative processing (e.g., rote or elaborative rehearsal of learned items), (3) study time (e.g., slow rate of presentation of study materials), and (4) modality shifts between learning and test.

However, there is currently no agreement in that perceptual priming operates according to different principles than explicit tests such as recognition or recall. On the one hand, for example, Ratcliff and Mckoon (1995; 1996) have argued that repetition priming effects only reflect general bias and not enhanced processing or facilitation. These claims have been based on a variety of tasks such as word identification, object decision, word stem completion, and picture naming. The core evidence is that in tasks in which a similar lure item (e.g., *lie*) relative to a target item (e.g., *die*) has been studied, participants perform worse than when neither alternative has been studied. On the other hand, it has been also shown (with similar tasks) that participants are able to show not only bias but also discriminability between targets and lures when low frequency words are used (Zeelenberg, et al., 2002). These latter findings posit constraints for both dual and single learning approaches (e.g., dual theories should be extended to account for bias and unitary theories should be modified to account for low-frequency word effects). In sum, the question of whether implicit memory effects such as repetition priming operate according to different rules than explicit learning is a debate in progress.

3.3 Representation of information

During the late 80's and early 90's, a body of experimental evidence reported systematic differences between implicit and explicit memory tests when the format (e.g., visual vs. acoustic, skills vs. facts, abstract vs. specific) in which information was presented to participants was manipulated. In 1993, two reviews, one positive toward the multiple-systems perspective (Schacter, et al., 1993) and the other oriented to the transfer-appropriate-processing perspective (Roediger and McDermott, 1993), attempted to summarize the empirical evidence . I abridge here what is known about the effects of key variables on the form of information representation. The essential question here is whether different memory systems store and represent information in different codes. More specifically, whether there is evidence that the implicit memory system stores information in highly specific codes whereas the explicit memory system store information in abstract or generalized codes.

3.3.1 Word picture manipulations

Critical evidence of dissociations between implicit and explicit memory has been reported comparing verbal and nonverbal implicit tests. On the one hand, there are 4 variants of verbal implicit tests. (1) stem completion, in which participants are given a number of letters with multiple possible completions and are asked to provide the first word that comes to mind [e.g. for~ (forest)]; (2) fragment completion, in which word fragments with one or two possible completions are provided with similar instructions [e.g. f-r-s-(forest)]; (3) word or perceptual identification, in which target items are exposed for brief durations (e.g. 35 ms), and participants attempt to identify them; and (4) lexical decision, in which participants are shown letter strings that constitute real words or nonwords (e.g. flig) and are asked to make a word/nonword decision as quickly possible. On the first three tasks, priming is indicated when subjects complete or identify more studied than nonstudied items; on the fourth task, priming is indicated when subjects make lexical decisions about studied items more quickly than about nonstudied items.

On the other hand, there are 4 forms of nonverbal implicit tests: (1) picture naming, in which participants name previously presented pictures as quickly as possible; (2) picture fragment completion, in which participants are given fragmented versions of pictures and asked to identify them; (3) object decision, in which participants are shown drawings of real and impossible objects and are asked to make object/nonobject decisions; and (4) dot pattern identification, in which participants are exposed to degraded versions of dot patterns that they either copy or complete. In all cases, priming is indicated by greater accuracy or reduced latency for studied items relative to nonstudied items.

On verbal implicit tests, words produce more priming than pictures. On nonverbal tests, pictures produce more priming than words (e.g., Weldon, 1991). Hence, it appears that implicit tests are strongly dependent on the overlap of formats between encoding and testing. These findings with implicit tests remarkably differ from findings with standard explicit tests that usually find an overall superiority in memory for pictures under a broad range of manipulations and variables (e.g., Park, et al., 1983; Standing, 1973). In general, picture word manipulations support the idea that implicit memory is encoded in highly specific formats.

3.3.2 Priming for words in bilinguals

The experimental setting used to study priming for words in bilinguals consists in preexposing participants to a list of words in the first language and then testing their implicit memory (e.g. using a lexical decision task) with a set of words from the alternate language. The interesting question addressed here is whether bilinguals presented with a word in one language are capable of showing transfer of priming effects when the test is given in the other language. However, the answer seems to be negative. The empirical evidence shows that language specific lexical processes mediate priming only on perceptual implicit memory tests; thus the word form (not the word's meaning) is what produces priming in bilinguals. This finding has been obtained not only in lexical decision tasks, but also in word fragment completion, and word stem completion (see, Roediger and McDermott, 1993: for an overview). Again, this finding supports the assumption of a separated implicit memory system which processes information in a specific format.

3.3.3 Lexical variables

Lexical variables refer to natural variations of lexical properties of words in a natural language. These natural variations are typically preexperimentally estimated from production norms obtained from large groups. The most studied variable has been word frequency in English language, but other lexical variables such as distinctive orthography or the number of graphemically similar words have also been studied. The typical experimental setting to study lexical variables consists in requiring participants to learn for example high frequency and low frequency words and testing their knowledge of the words with explicit tests (e.g. recall) or implicit tests (word completion). A typical finding is that performance on implicit tests is better for low frequency words, whereas performance on explicit tests is better for high frequency words. Investigating these variables is relevant to multiple-system accounts because they appear to affect performance only on verbal perceptual tests, in agreement with the idea that implicit memory is supported by a word form memory system. Indeed, regarding word frequency and distinctive orthographically words, according to Roediger and McDermott (1993), it appears safe to conclude that special words (e.g., rarely encountered in every day speech) tend to produce more priming than high frequency words or common words.

3.3.4 Manipulations of modality

Manipulations of modality involve an experimental alteration in surface features between study and test presentations of the experimental materials. The most common manipulations, for example, consists in auditory tests with words that have been previously learned in a visual modality. However some other manipulations may involve variations in the typography (e.g., font or case) or presentations as intact or degraded forms of the words. These sort of manipulations are relevant for the multiple-system approach because they are used as evidence for the assumption of a modality specific subsystem for auditory and visual information.

In fact, it has been demonstrated that testing in the same modality preserves priming in a broad range of manipulations and tasks such as stem completion, word identification, and word fragment completion. Currently, there appears to be little doubt about the supremacy of perceptual priming in tests with a modality overlap (e.g., visual-visual or auditory-auditory). Additionally, it has been observed that manipulations within the same modality involving changes in typografy (e.g., learning words in “times new roman” and testing in “arial” fonts) have less effects than changes in cross-modalities situations (Roediger and McDermott, 1993).

3.3.5 Physical variations

Do variations in physical characteristics of pictures affect transfer of priming? For example, when participants study a picture of a house and are later tested with a different exemplar? This sort of experimental manipulation is used to test whether implicit information is represented in abstract or specific codes. If priming is assumed to be a purely perceptual phenomenon, as assumed by the multiple-system view, then tasks such as picture naming, object decision, and naming picture-fragments should reveal specificity effects (this is, absence of transfer). Indeed, in most tasks, some manipulations like pictorial examples, visual orientation, picture depth etc., reveal specificity of priming although other manipulations such as changing the size or the reflection (e.g., left-right orientation or mirror reversal) do not affect priming but affect recognition (Cooper, et al., 1992). These latter findings (manipulations of size and reflection) are a challenge to multiple system views because they show an inverted pattern of results, that is, recognition is affected by variations in perceptual characteristics but priming is relatively spared.

Another physical variation is auditory. For example, studies on the effect of changing the voice of the speaker, agree with findings from visual studies in that priming is better when the same perceptual characteristics are maintained (e.g., Schacter and Church, 1992). However, later studies have shown that the overlap between encoding and testing tasks is more relevant than the mere physical variation of acoustic properties (Sheffert, 1998).

Taken together, the findings from visual and auditory variations of stimuli do support the assumption of an implicit memory system with two different subsystems responsible for processing exclusively either visual or acoustic forms of information.

To summarize, in several tasks involving manipulations on the form of representation of information, implicit measures of memory behave differently than explicit measures. There is agreement that modifying the surface structure of stimuli has an effect on implicit memory but no comparable effects on explicit memory. Thus, supporting the assumption that implicit memory relies on highly specific codes. Conversely, manipulations of deeper processing tend to strongly affect explicit tests but do not affect implicit measures. However, there is no agreement in that these dissociations necessarily point to the fact that repetition priming is based on specific formats requiring precise instances or episodes (Bowers, 2000; Tenpenny, 1995). For example, it has been argued that the crucial factor to explain the above mentioned dissociations is the degree of overlap between cognitive operations required at learning and cognitive operations required at retrieval (e.g., Roediger, 1990).

3.4 Development

In this section, I summarize the empirical evidence for the proposal that implicit forms of knowledge such as perceptual and motor skills, maturate earlier in ontogeny and phylogeny than explicit forms of memory.

3.4.1 Ontogeny

The fundamental reason to search for different developmental patterns of implicit and explicit learning and memory is the hypothesis that implicit learning and memory appear to depend on evolutionarily primitive functions and should therefore demonstrate early ontogenetic maturation and robustness across the life-span. This hypothesis constitute the so called *developmental invariance assumption* of implicit memory (Reber, 1993).

Three sorts of evidence have been provided in support of this view (Nelson, et al., 2006). First, implicit forms of learning and memory seem to appear earlier in ontogeny than forms of explicit processing. For example, Clohessy, Posner, and Rothbart (2001) studied anticipatory eye-movements involved in the learning of simple and complex (context dependent) sequences in children of 4 months, 10 months, 18 months, and young adults. They found that the ability to learn simple sequences was already present in the 4th month but that context-dependent sequences were learned only after the 18th month (see also, Ausley and Guttentag, 1993; Lorsbach and Morris, 1991). The authors suggested that the learning of unambiguous sequences by 4-month-olds reflects maturation of a basal ganglia–parietal circuit related to adult implicit learning, while the learning of context dependent sequences requires development of frontal structures underlying more general attentional abilities.

A second sort of evidence concerns dissociations in maturation. Performance on implicit tasks seems relatively stable at most maturation stages whereas performance on implicit tasks displays important differences across childhood and adolescence (Jelicic, 1996; Meulemans, et al., 1998; Naito, 1990). For example, Naito (1990) compared implicit memory on word-fragment completion tests with explicit memory performance on recall and recognition tests in participants of 7 years, 12 years, and young adults. He found that participants' age did not affect priming performance but explicit performance on recall and recognition tests improved with age.

A third sort of evidence that appears to support the invariance assumption concerns dissociations in aging (e.g., Howard and Howard, 1989; e.g., Mitchell and Bruss, 2003). Older participants appear to retain implicit learning and memory abilities but explicit memory performance seems to decrease with age. For instance, Howard and Howard (1989) reported a dissociation between priming in a SRT task and explicit memory in a generation tasks were young (22 years-old, in average) and old participants (71 years-old, in average) were compared. They reported no significant difference in the learning of the implicit task between age groups but a reliable age difference was found on the (explicit) generation task.

However, all three kinds of evidence have been either challenged by more recent evidence or by alternative interpretations of the results (e.g., Cycowicz, 2000; Rovee-Collier, 1997). For example, Rovee-Collier (1997) has presented empirical evidence obtained with preverbal infants that refutes the notion that two separable and functionally distinct memory systems mature at different rates. She showed that very young infants (up to 1 year-old) demonstrate memory dissociations that resemble those exhibited by adults with normal memory on explicit and implicit tasks. To compensate the fact that prelinguistic infants lack verbal responses to resolve the explicit tasks, participants are first trained on a motoric operant response (e.g., foot-kick) that they can subsequently use to indicated whether or not they recognize a test stimulus. Infants explicit (yes-no) recognition is measured by an increase (indicating a “yes” response) or a decrease (indicating a “no” response) in the motoric operant response relative to their individual baseline. In the implicit tasks, subcomponents of (a) pre-trained stimuli and (b) novel stimuli are then briefly interpolated between the baseline and the test, priming is revealed when performance during test for interpolated stimuli is better than performance for novel materials.

Moreoever, recent evidence has shown that the neural substrates apparently relevant for implicit memory processing (i.e., caudate nucleus) seem to undergo maturation during late childhood and adolescence (Casey, et al., 2004). This finding may be interpreted as evidence against the developmental invariance assumption, because imply that the implicit memory system is more plastic across life span than previously thought.

There are also demonstrations that non verbal explicit forms of memory and learning (e.g., elicited imitation) may be available quite early in infancy, which contradicts the assumption that only implicit forms of memory emerge early in ontogeny. Explicit forms of memory based on elicited imitation tasks demonstrate clear developmental and age-related improvements across childhood but are not necessarily comparable with verbal memory (Bauer, et al., 2002; Bauer, et al., 2003). Additionally, implicit memory has been revealed to be age dependent when the knowledge on which memory is based is also undergoing parallel development (Murphy, et al., 2003), which implies that the apparent invariability of implicit memory, previously reported across the lifespan, may be an artifact produced by highly stereotyped or familiar stimulus materials.

In sum, the developmental invariance assumption of implicit knowledge has been strongly challenged by at least two different sources of evidence. At present, it does not appear safe to conclude that implicit memory develops earlier than explicit memory.

3.4.2 Phylogeny

Another keystone for the postulation of multiple systems is the assumption that implicit forms of memory may be phylogenetically older in contrast with explicit forms of memory (Sherry and Schacter, 1987). This assumption is based on the suggestion that different specialized adaptive functions (i.e., implicit and explicit memory) are shaped by principles of natural selection. One of these principles is that of *functional incompatibility*, this is, when the adaptation to one type of environmental problem turns to be incompatible with a different environmental problem. A common example used in evolutionary biology to illustrate the principle of functional incompatibility is that most flying insects have two different kinds of eyes. Composed eyes that probably enable the insect to have a wide field of view and simple eyes that appear to help on navigation.

The core idea applied to the multiple-system approach is that the implicit memory system has developed earlier in phylogeny to support gradual learning involved in the acquisition of skills and habits whereas the explicit memory system has developed later in phylogeny to support rapid one-trial learning and to form memories of specific situations (see Section 3.1). In this regard, there is agreement that animals are capable of implicit forms of memory such as perceptual learning or memory for skills and habits.

Empirical evidence of phylogenetically old forms of implicit memory have been extensively reported and studied (Sahley and Crow, 1998). A form of memory similar to perceptual priming has been found in invertebrates by studying the nature of the information used by bees in remembering flower shapes (Cartwright and Collett, 1982; Gould, 1988; Thivierge, et al., 2002; Wehner, 1972). For example, Thivierge, Plowright, and Chan (2002) trained bees to discriminate complete patterns indicating the presence or absence of food (e.g., circle, star), during test, bees were presented with portions of the learned patterns and full patterns. The results showed that bees were able to remember most of full patterns and were also able to transfer the discrimination performance to some incomplete patterns. From these studies it appears safe to conclude that bees can remember images of landmarks relevant for foraging. Similarly, Gould (1985) found that bees were able to remember different patterns that differed primarily in the spatial relations among the elements. For example, bees responded similarly to mirror-images of simple patterns but discriminated between rotations of vertical patterns.

Despite the fact that a new body of evidence indicates that mammalians may also be able to show explicit forms of memory (Clayton and Dickinson, 1998; Clayton, et al., 2001; Kart-Teke, et al., 2006), this sort of evidence neither proves that explicit forms of memory are phylogenetically older (or equally old) than implicit forms of memory nor do they challenge the principle of functional incompatibility. Additionally, some scholars remain cautious about comparisons between human episodic memory and animal "episodic-like" memory (Morris, 2001; Suddendorf and Busby, 2003) because the latter do not meet the strict criteria required for episodic memory (i.e., autonoetic consciousness and language). Therefore, it appears that current evidence supports the assumption that implicit forms of memory developed earlier in phylogeny than did explicit forms.

3.5 Neural substrates

Multiple-systems approaches in implicit memory have heavily relied on neuropsychological studies of patients with memory disorders and neuroscientific data collection techniques (e.g., Milner, et al., 1998; Schacter and Badgaiyan, 2001; Squire, 2004). Indeed, such an approach is crucial to the multiple-systems perspective because one definitional property of a separable system is the assumption that implicit memory must be instantiated in a different brain substrate than the explicit system. In this section,I summarize what is known about the assumption that different neural substrates support explicit and explicit memory systems.

As briefly mentioned before, one of the first sources of evidence for implicit memory in neuropsychology arose from the amnesic patient known as H.M. Despite having undergone a resection of the medial temporal lobes, this patient was able to learn a motor skill (mirror drawing) in the absence of any memory of having practiced the task before (Milner, et al., 1968). More recent evidence indicates a preserved ability to learn other complex perceptual-motor skills in amnesic patients (Cavaco, et al., 2004). Similarly, the work of Warrington and Weiskrantz (1968; 1970) showed that amnesic patients are able to perform as well as normal participants in some implicit tasks (stem completion) when the instructions do not contain any reference to memory retrieval (e.g., respond with the first word that comes to mind); but amnesic patients perform worse than control participants when they are instructed to explicitly retrieve the words. These findings were subsequently widely replicated and extended to other tasks (Diamond and Rozin, 1984; Graf, et al., 1984). Taken together, this evidence was used to suggest that the hippocampus and related brain regions, typically damaged in amnesic patients, are strongly correlated with performance on explicit memory tests. In fact, during the 90's, most multiple-system perspectives on memory converged in the assumption that the hippocampus was crucial for performance in explicit memory (Schacter and Tulving, 1994). However, some later neuroimaging studies have emphasized that the most probable role of the hippocampal system is in memory binding or relational memory processing (Cohen, et al., 1999) but not in directly priming performance. A systematic comparison of perceptual and conceptual implicit tasks in Alzheimer's patients has shown that implicit tests involving purely perceptual priming (word-identification, and word-stem completion) do not correlate with the neuropathological level of severity of the illness (Fleischman, et al., 2005).

As has been noted by Schacter (Schacter and Badgaiyan, 2001), studies of amnesic patients cannot clarify the brain substrate of implicit memory; they can only show which brain regions are important for explicit memory. More recent studies have attempted to answer this question by analyzing the activation patterns observed during implicit retrieval tasks. Although there is some discussion about the necessity to distinguish the role of intention to remember from the role of awareness to remember in implicit tasks (Schott, et al., 2005), most studies appear to converge in demonstrating that implicit tasks correlate with *decreased* activity in the extratriate area of the visual cortex, an area thought to play an important role in perceptual learning (Schacter and Badgaiyan, 2001; Schacter, et al., 2007; Wiggs and Martin, 1998). In this regard, it is interesting to note how the discussion in cognitive neuroscience parallels the discussion in cognitive psychology about the criteria needed to assert that dissociations warrant the assumption of a memory system. For example, recent findings have shown that implicit and explicit memory are correlated in behavioral and brain mechanisms at encoding (Turk-Browne, et al., 2006) but some other studies have found that explicit and implicit memory are dissociated (Schott, et al., 2006). Currently, mixed explanations have been proposed in which implicit and explicit knowledge are acquired by a common mechanism but are differentiated in the way the systems access the stored representations (Turk-Browne, et al., 2006).

At the time of the present review no further neuroimaging experiments had studied the additional subdivisions of the implicit/explicit taxonomy (e.g. visual representation system vs auditory representation system). Rather, a review of neuroimaging studies of priming has revisited the same problems encountered in cognitive psychology about the contamination problem (Henson, 2003). What is clear is that a host of research with neuroimaging techniques may be still required to understand the neural correlates of memory in general and of implicit memory in particular.

3.6 Forgetting

In this section I summarize the experimental evidence concerning forgetting patterns of implicit and explicit knowledge. I focus, first on research originated from implicit memory research and later on implicit learning research. Some authors have suggested that research on implicit memory and research on implicit learning should be logically related (e.g., Berry and Dienes, 1991) to achieve a unified theoretical account of the processes underlying the acquisition and retrieval of implicit information. In practice, however, each field has developed a different set of research paradigms adapted to different goals and methodologies. On the one hand, memory research has largely benefited from investigations with amnesic patients, and has been intensely interested in paradigms producing perceptual priming such as word-stem completion, word identification, and related phenomena. In the forthcoming section, I survey evidence that makes use of perceptual priming but also of the process dissociation procedure, the perceptual identification task, the remember/know paradigm, and that compares performance on objective measures such as recognition and subjective measures such as confidence ratings.

On the other hand, in the section dedicated to implicit learning research, I include studies approaching the problem of retention rates of implicit and explicit knowledge with paradigms traditionally used in this area. These are, artificial grammars (e.g., verbalizations versus classification), production rules, process dissociation procedure (applied to artificial grammars), and recognition memory. The boundary between research on learning and memory is only used here as a provisional criterion to organize the review, but it does not necessarily imply that studies need to be classified in this manner.

3.6.1 Memory Research

Originally, research on implicit memory was interested in understanding dissociations between implicit and explicit tests observed in amnesic patients. In fact, amnesic patients appeared to show normal forgetting patterns on implicit memory tests but impaired memory in explicit tests (Graf, et al., 1984). Most of these early studies used stem completion as the implicit task and recognition as the explicit task. For example, performance for stem completion was significantly above chance during an immediate test and after 15 minutes but performance on recognition tests declined to chance after 15 minutes (Graf, et al., 1984). However, the replication and extension of such findings to normal participants and to other tasks has been questionable. Roediger and McDermott (1993) comprehensively revised the early research (1981-1992) concerning the effects of retention intervals on implicit memory; they concluded that “any claim of implicit memory measures being especially resistant to forgetting has been conclusively disconfirmed” (p. 113).

Subsequent research was based on the consideration that previous differences reported between implicit and explicit tests (e.g., stem completion and recognition) may be due to the fact that the two measures differ in level of difficulty. Indeed, one problem in comparing stem completion and recognition tasks is that they diverge fundamentally in the kind of response they require. In recognition, a test item is given to the participant and the response is largely based on familiarity to the item. On the other hand, stem completion requires a productive response, that is to say, the participant generates a completion to the presented cue.

For these reasons, McBride and Dosher (1997) compared forgetting rates for performance on a stem-completion (implicit) task with performance on a stem-cued recall (explicit) task. In these studies (McBride and Dosher, 1997), the two tasks differed only in the instructions, but kept the stimulus and response format equal. This was done in order to satisfy the retrieval intentionality criterion for valid comparisons of implicit and explicit task performance (Reingold and Merikle, 1988; Schacter, et al., 1989). The experimental manipulation included retention intervals between 1 and 90 minutes. Contrary to the prevailing evidence found with amnesic patients, McBride and Doscher (1997) found that both the explicit and the implicit measures showed an equivalent pattern of forgetting in normal subjects. Similarly, in two follow-up experiments the same researchers (McBride, et al., 2001) found comparable forgetting on implicit and explicit tests. In the first experiment, a word-fragment completion tasks was introduced under implicit and explicit instructions. In the second experiment, the process-dissociation procedure was used to control for possible contamination on the implicit task by implicit retrieval (Jacoby, 1991). In accordance to Jacoby's process dissociation procedure, inclusion and exclusion fragment completion tasks were implemented. For the inclusion task, participants were instructed to complete fragments with a word they had studied; for the exclusion task, the instructions were to complete the fragment with an item that they had not studied in the experiment. Taken together, this line of research showed that implicit and explicit knowledge seem to be forgotten at similar rates in short (up to 90 minutes) retention intervals.

However, a further study also used the process-dissociation procedure (Stolz and Merikle, 2000) but found that when retention intervals are considerably extended up to delays of 2 months, explicit memory decreases steadily but implicit memory first increases and then remains relatively stable from 2 days to 2 months. The results highlighted the importance of using longer retention intervals to observe dissociations in forgetting of implicit and explicit memory tests. Nevertheless, the process-dissociation framework was the object of intense debate (Erdfelder and Buchner, 2003). For example, another study by Wilson and Horton (2002), has shown that the increase in implicit memory reported at the shorter intervals of Stolz and Merikle's (2000) study may be an artifact of the process-dissociation procedure. Apparently, the process-dissociation procedure underestimates the automatic retrieval component in the shorter retention intervals. However, this result did not question the finding that explicit influences on memory tend to decay more rapidly than implicit influences over longer intervals.

Further evidence of dissociations between implicit and explicit memory has been obtained with conceptual tests that provide a retrieval cue that is semantically related to a previously studied word (Goshen-Gottstein and Kempinsky, 2001). In this experiment, implicit memory performance (a test without reference to the study episode) remained stable across five different retention intervals (up to 3 weeks) whereas explicit memory performance decreased systematically. Interestingly, explicit performance was initially about two times higher than implicit performance but after 3 weeks performance was equal in the two tasks. Additionally, the forgetting curves for implicit and explicit knowledge were successfully fit to logarithmic functions on which the amount of information that was lost on the explicit test was approximately six times greater than that on the implicit test. The authors argued that these results are consistent with a dual-system interpretation wherein an episodic system supports memory on the explicit task and a semantic system supports memory on the implicit task.

Another convergent line of evidence has originated within the remember/know paradigm framework (Gardiner and Richardson-Klavehn, 2000; Tulving, 1985). This paradigm attempts to dissociate the recollective and familiarity components of binary recognition judgments. The basic assumption is that recognition tests can be accompanied by either (a) conscious recollection of some specific experience, or (b) feelings of familiarity without any recollective experience. Participants are instructed to provide a “remember” response when the test item brings back to mind some specific recollection of what was experienced when the item was initially studied. A “know” response is to be provided when the item brings to mind feelings of familiarity without any recollective experience. Two experiments (Gardiner and Java, 1991) showed that these two forms of recognition have different forgetting rates. Recognition accompanied by recollective experience is initially higher but declines soon over a 24-hour period. In contrast, recognition without recollective experience shows little forgetting over the first 24 hours. Subsequently, both kinds of recognition memory decline gradually at about the same rate. The authors interpreted these results as evidence against the idea that dissociations between “remember” and “know” responses are based on strong and weak memory traces that might be accounted for from a single-system perspective (cf. Wagner, et al., 2005; Wixted and Stretch, 2004). Additionally, the authors also suggested that a possible reason for the difference in forgetting functions for "remember and "know" responses is that of differential susceptibility to *interference* because other priming effects in implicit memory such as fragment completion also seem relatively immune to interference (e.g., Sloman, et al., 1988; experiment 5).

More recently, it has been shown that priming involved in a picture-fragment identification test may last up to 17 years (Mitchell, 2006). However, in this study no objective concurrent measure of explicit memory was collected after the retention interval, so it is not possible to compare the retention rates of the 2 forms of knowledge.

To summarize, early evidence (1981-1992) reporting dissociations in the forgetting patterns of implicit and explicit tasks has been criticized because the two tasks arguable differ in the level of difficulty. In fact, more recent evidence shows that dissociations between implicit and explicit tests may be due to the fact that each test yields different reliabilities. More precisely, word-stem completion tasks (implicit tests) seem to be less reliable than explicit test such as yes-no recognition (Buchner and Wippich, 2000). It remains an open question, however, whether reliability also changes with time and whether the general argument applies to different tasks such as artificial grammar learning and serial response time tasks.

Subsequent experiments in which the implicit and the explicit tasks were equated in all relevant aspects except the instructions, showed similar patterns of forgetting on implicit and explicit knowledge for shorter intervals (up to 90 minutes). However, different forgetting patterns for implicit and explicit knowledge were found when the retention intervals were extended up to 2 months. Unfortunately, this evidence may be susceptible of criticism because it is based on the process-dissociation procedure.

Finally, additional evidence of dissociations in the forgetting patterns of implicit and explicit knowledge has been also reported with (1) conceptual tests and (2) with the remember/know paradigm. However, both findings are difficult to interpret from the multiple-system perspective. On the one hand, dissociations between implicit and explicit conceptual tests are similarly predicted by two competing theories: the transfer-appropriate-processing framework and the multiple-system framework; clearly, more empirical research is needed to understand why conceptual tests and perceptual tests of implicit memory yield different results.

On the other hand, the remember/know paradigm has made it clear that recognition judgments may be influenced by both implicit and explicit knowledge. This fact confirms the idea that binary recognition judgments, originally considered a pure measure of explicit knowledge, probably have to be partitioned to detect implicit and explicit components. This constitutes a good reason to use a form of metacognitive judgment in order to disentangle the implicit and explicit influences on tests using binary recognition judgments. Therefore, in the empirical part of this dissertation I make use of a similar technique by requiring participants to provide a confidence rating after every recognition judgment.

3.6.2 Learning research

In this section, I review the evidence conducted with the traditional materials of implicit learning research that is concerned with comparisons of the retention rates of implicit and explicit knowledge. Specifically, I evaluate evidence collected with the artificial grammar task, production systems, and the SRT task.

Allen and Reber (1980) were the first to provide evidence supporting the idea that explicit knowledge about artificial grammars seems relatively fragile to the passage of time whereas implicit knowledge seems to be quite robust. These authors conducted an experiment in which participants learned two different artificial grammars. The first grammar was learned by relating grammatical strings with names of cities using a paired-associated procedure. The second grammar was learned using an observation procedure in which participants simply attended to a series of exemplars without further specific instructions. Participants were tested immediately after completion of the learning phase and after two years. During tests, participants' knowledge was assessed with a well-formedness task by requiring them to judge the grammaticality of many new (correct and incorrect) and some old sequences. Additionally, participants provided extensive introspective verbal descriptions about the way they had learned the original materials. The authors concluded that most retained knowledge was implicit because participants were not able to verbalize much about the structure of the underlying grammars although they performed above chance in the classification task after two years.

However, one problem with this experiment is that it was not initially devised for evaluating and comparing the temporal patterns of implicit and explicit knowledge (Reber and Allen, 1978). Rather, it was originally conceived to demonstrate that besides analogical knowledge conveyed by the paired-associated procedure (Brooks, 1978), participants were capable of forming abstract representations of an artificial grammar. The authors' basic claim that implicit knowledge is better retained than explicit knowledge rests on the assumption that implicit knowledge is abstract in nature and that the observation task mainly conveyed acquisition of abstract information. Thus, given that some abstract knowledge was retained after the retention interval, the authors assumed that most retained knowledge must have been implicit.

There are some additional problems with this experiment and the way these results are interpreted. These issues are mainly related to the selective influence criterion and the sensitivity criterion explained in Section 2.3. First, both the paired-associated and the observation tasks are presumed to equally originate from implicit and explicit knowledge, therefore the decrease in overall performance may be attributed to a loss of both explicit and implicit information. Second, the introspective reports were not quantified in any form, which makes it impossible to estimate the decrease of explicit knowledge over time. Third, there is no way to assure that the well-formedness task constitutes a measure of implicit or explicit knowledge. Fourth, and perhaps most importantly, there is now convincing evidence showing that a well-formedness (transfer) task may be successfully accomplished on the basis of fragmentary information about the learned strings (Dulany, et al., 1984). Therefore, the argument that most of the retained knowledge is implicit in nature does not hold.

Another interesting piece of evidence has shown that implicit knowledge may be more robust than explicit knowledge (Lee and Vakoch, 1996) by taking advantage of the system-production paradigm (e.g., Broadbent, et al., 1986). In this experiment, participants learned to produce target values by entering input values into a computer. Unknown to the participants was the fact that underlying simple or complex equations computed the output value as follows:

Complex equations:

Output 1 = (3.5 x input 1) + (4 x input 2)

Output2 = (7.5 x input 2) – (0.7 x input 1)

Simple equations:

Output 1 = 0.5 x input 2

Output 2 = 3 x input 1

After reaching a learning criterion, participants' explicit knowledge was assessed via multiple choice questions designed to test their acquired knowledge of the quantitative relationships between input and output. Implicit knowledge was assessed by requiring participants to perform transfer tests similar to the ones used for the learning phase. Importantly, the information relevant to successfully resolve the implicit test matched the questions used for the explicit test because both tasks required the same knowledge-base to be effectively resolved, which provides an elegant way to deal with the information criterion (Shanks & St John 1994). The results showed that when participants were tested immediately after the learning phase, scores from performance test were reliably higher than scores from the questionnaire for the complex task. This particular finding implies that the complex task requires a greater proportion of implicit knowledge. On the other hand, for the simple task, the difference between explicit and explicit tests were not reliably different from zero, indicating that the simple task mainly involved explicit knowledge. More interestingly, when participants were tested one week later, scores on the simple task (requiring mainly explicit knowledge) were significantly lower, whereas scores on the complex task (requiring mainly implicit knowledge) showed no decline. Taken together, the results are interpreted as indicating that participants' explicit knowledge declined and their implicit knowledge remained at the same level when retested one week later. However, the authors also pointed out a potential problem with this data. Because there was no significant interaction between task type and time, it is possible that the null effect of time on the complex task was due to a lack of sensitivity.

The findings reported by Lee and Vakoch (1996) have been interpreted as being consistent with multiple-system accounts because they may reflect two sources of knowledge that are differently affected by the passage of time. For the goals of the present dissertation it is important to note that despite the importance of this kind of finding, no specific mechanism to account for this sort of dissociation have been proposed.

Another study (Higham, et al., 2000) adopted the opposition logic, mainly developed within the field of implicit memory (Jacoby, 1991; Jacoby, et al., 1993), to the materials traditionally used for research on implicit learning. In an attempt to overcome the difficulties inherent in the dissociation logic, these authors provided evidence indicating that a retention interval (Experiment 2) may have differential effects on implicit (uncontrolled) recognition judgments compared to explicit (controlled) recognition judgments. Higham, Vokey and Pritchard (2000) asked participants to study two different sets of letter strings generated from two different grammars (GA and GB). Participants were tested immediately after learning and after 12 days. During each test, in the consistent (C) condition, participants were required to decide whether new grammatical and ungrammatical strings belonged to grammar A, to grammar B, or to neither grammar. In the opposition (O) condition, participants were required to classify strings only from one of the artificial grammars as grammatical or ungrammatical. Therefore, in this experiment, the assignment rate for items from one of the previously trained grammars to the opposite category constitutes the opposition condition (i.e., assigning items of GA to the B response category or conversely, assigning items of GB to the A response category). The authors found that the acceptance rate for grammatical items in the opposition condition was stable after the 12-day retention interval but the acceptance rate for grammatical items in the consistent condition decreased significantly. Additionally, the endorsement rates for the baseline (B) were lower than for both the C and O conditions. In other words, the general pattern of results was: C > O > B. The fact that participants were not consciously able to avoid assigning a correct item to a correct category in the opposite condition, is normally assumed as evidence of uncontrolled processing in the classification task within the opposition logic framework. That is, the implicit (uncontrolled assignment of items of the correct category in the opposition condition) component of recognition judgments appeared to be relatively immune to the retention interval, whereas the controlled (explicit) responding component was impaired. This finding also appears consistent with the operation of two separable influences on classification performance (a) familiarity and (b) recollection, which are assumed to operate in parallel. However, in a later reply to a commentary (Redington, 2000), Higham and Vokey (2000) advocated a single process account according to which the controlled and automatic influences revealed in their data were manifestations of a common underlying episodic-processing system (Higham and Vokey, 2000). However, this account did not specifically describe the mechanism responsible for the dissociation.

At the present time there is no agreement on whether such results may be better accommodated by single-system or multiple-system models. Tunney and Shanks (2000) and Redington (2000) have argued that the pattern of results C > O >

B simply reveals that GA-items and GB-items are similar to each other, whereas ungrammatical items are distinctive. Therefore, the retention interval serves to make classification more difficult, which virtually eliminates the controlled effects because it is dependent on the difficult discrimination between grammars. In turn, automatic influences are assumed to be left intact because the discrimination between grammatical and ungrammatical items is easy. Additionally, the pattern of results C > O > B was successfully modeled (Tunney and Shanks, 2003) by a single-system connectionist model that does not assume in its architecture different (i.e., automatic vs. controlled) influences on performance. The single-system model was constructed by adapting the Simple Recurrent Network (Cleeremans, 1993; Cleeremans and McClelland, 1991; Cleeremans, et al., 1989) to this experimental manipulation. However, as noted by Vokey and Higham (2004) this model did not simulate the magnitude of the dissociation to the same extent demonstrated in the empirical data. Alternatively, another model (Vokey and Higham, 2004), based on an auto associative network (Abdi, et al., 1999) closely simulated the empirical dissociation indices originally obtained. The core assumption of this model in simulating the empirical results was that both the automatic and the controlled influences are necessary in grammaticality recognition judgments (GA and GB items versus NG items), but only controlled influences are necessary for the discrimination between GA and GB.

However, a serious difficulty with this line of research is again that the relationship between the opposition logic and dual-process models of memory are a source of considerable debate (Buchner, Erdfelder, & Vaterrodt-Plunnecke, 1995; Erdfelder & Buchner, 2003). For example, the effect of other motivational tendencies such as bias may influence performance but may not be correctly estimated with the opposition logic framework.

A more recent study (Tunney and Bezzina, 2007) has obtained similar dissociations in the forgetting rates of recollection and familiarity, using strings of letters generated by artificial grammars. In this study, participants provided recognition and confidence judgements for studied items. Tests were conducted immediately after learning, after 7 days, and after 14 days. The confidence ratings were analysed via receiver operating characteristics (ROC) in order to reveal the extent to which both recollection and familiarity contributed to recognition. Within the ROC framework for analysing recollection and familiarity (Yonelinas, 1994;

Yonelinas, 1997), it is assumed that ROC curves that plot the transformed z-scores of hit rates against z-scores of false alarms for different levels of confidence may reveal the relative contribution of implicit and explicit components when their slopes deviate from 1. The underlying rationale is that ROC curves with slopes close to 1 are perfectly described by a single signal-detection model of memory (e.g., Morrell, et al., 2002) in which recognition performance is based exclusively on the signal's strength (e.g., familiarity), whereas systematic slope deviations from 1 imply that high confidence ratings associated with recollection also influence recognition performance. The authors found that during the first test the slope was reliably different from 1 but in the subsequent tests conducted after 7 and 14 days the slope was not reliably different from 1 indicating that recollection had declined and recognition was based on familiarity alone. However, the authors interpreted the data by assuming that familiarity also represents an explicit memory process and that the dissociation may be modeled by varying specific parameters that govern the sensitivity of recollective and familiarity components.

Another relevant piece of evidence shows that the implicit status does not confer absolute invulnerability to a memory trace. Willingham and Dumas (1997) studied the maintenance of a motor skill in a SRT task after a retention interval of one year. In their study, participants learned 12-unit sequences and were tested immediately after learning and after one year. The results showed that compared to a control group, specific motor sequence knowledge was not retained. Similarly, additional measures of explicit knowledge, such as free recall and recognition, also decreased significantly. This study suggests that implicit motor knowledge is also lost over time but is not informative about the issue of whether or not it differs from other explicit measures such as recognition and recall.

Finally, a piece of evidence especially relevant for the present dissertation has shown that implicit and explicit knowledge may decay at different rates (Tunney, 2003). This experiment was based on a matching task in which participants were asked to depress a key that corresponded to a single letter presented at the center of the screen. The letters presented to participants were based on an underlying artificial grammar. An initial learning phase was followed by three tests, one immediately following the learning phase, one administered 1 week later, and one administered 2 weeks later. For each test, old (grammatical) strings were mixed with new (ungrammatical) strings. During the test phases, participants provided two measures,

(a) response times to each letter of the strings, and (b) binary recognition judgments for every string. The implicit measure of knowledge was computed by subtracting RTs to old sequences from RTs to new sequences (RT priming). The explicit measure of knowledge was computed by subtracting z-scores for the proportion of new sequences incorrectly recognized from z-scores for the proportion of old sequences correctly endorsed (d'). The results showed that recognition d' had significantly decreased after a 1-week retention interval but RT priming prevailed. The effects did not appear to change from the second to the third time of testing.

Tunney (2003) pointed out that these results may be interpreted according to two different perspectives: from a dual-process perspective and from a single-process perspective. According to the dual-process perspective, reaction times remain constant and above chance because they are thought to be predominately supported by familiarity, whereas the lower recognition scores on tests conducted after the retention interval may reflect the decay of conscious recollection. Interpreted in this way these results would indicate the action of two different systems.

According to the single-process perspective, a unitary source of knowledge primes both motor and recognition responses. The dissociation would reflect different ways of responding but not the action of different learning or memory systems. Recognition would involve a decision whether to say either "old" or "new" and therefore may convey variability across various sensitivities and biases of participants. Motor responses, on the other hand, do not require such decisions to be made. According to this analysis, the dissociation is due to different ways of accessing the same knowledge base. For these reasons, Tunney (2003) also suggested, contrary to the common view, that priming may be a more direct test than recognition. This suggestion is extremely important for the analyses carried out in the simulation part of this dissertation, because it may imply that recognition suffers from a bigger error term than priming.

In summary, there is partial evidence in the implicit learning research indicating the possibility of a difference in the forgetting rates for implicit and explicit knowledge, which supports the multiple-system view. Especially appealing are the results obtained by Tunney (2003) because they may imply a set of empirical constraints to the competing single-system view. Consequently, a key issue that remains to be resolved is whether or not different sensitivities may be invoked to explain dissociations in the forgetting rates of implicit and explicit knowledge.

3.7 Summary

The existing empirical evidence seems to indicate that implicit knowledge (1) clearly fulfills different adaptive functions than explicit knowledge. (2) It also operates according to more basic, perceptual and motor, principles, and (3) it is found earlier in phylogeny. However, there are also a number of open questions. (1) It is not clear if implicit and explicit knowledge differ in the way they are represented by the cognitive system. (2) There are serious challenges to the developmental invariance assumption in ontogeny and (3) the study of the neural substrates of implicit memory is struggling to understand the general neural plasticity involved in the formation and retrieval of memories.

The previous appraisal of empirical evidence indicates that the "*retention criterion*", that is, the idea that studying and comparing the forgetting rates of implicit and explicit knowledge may play a significant role to decide between single-system and multiple-system theories of implicit knowledge. However, robust demonstrations confirming the retention criterion remain elusive. Only a few studies in implicit learning research have found evidence supporting the retention criterion (Lee and Vakoch, 1996; Tunney, 2003; Tunney and Bezzina, 2007), in particular, the study by Tunney (2003) has been based on an straightforward logic comparing the forgetting patterns of implicit and explicit measures from the same knowledge base (an artificial grammar). Therefore, a first key question concerns whether this finding may be independently replicated.

Even if robust evidence confirming the "retention criterion" is found, a second key question concerns whether a single-system theory assuming different sensitivities for implicit and explicit measures may adequately account for the differences in the retention patterns of implicit and explicit knowledge. To date, the interpretation of previous findings has left open to 2 alternatives. Either (1) the dissociations may be consistent with a multiple-system theory based on a body of evidence showing that implicit and implicit systems have different adaptive functions, governed by different operating principles and different developmental trajectories in ontogeny, or (2) the dissociations may be consistent with a single-system theory based on a body of evidence questioning the assumptions that implicit knowledge require different neural substrates, store information in a different format, and display different developmental patterns in ontogeny.

To elucidate the scope of the single-system assumption, I do not only ask whether implicit and explicit knowledge display different retention patterns, but I also ask whether the differences may be reasonably accounted for by a computational model assuming a single knowledge base. In sum, the empirical section shall present new empirical evidence of dissociations that (1) replicates previous findings, (2) extends previous findings to other experimental paradigms, and (3) tests the quantitative predictions of a single-system computational model.

4 Empirical Section

The broad goals of the empirical section are (1) to evaluate whether implicit and explicit knowledge differ in their forgetting patterns and (2) to test whether a single-system model may account for this special kind of dissociation. To this end, in Experiment 1, I started by conducting a replication of Tunney (2003). In this experiment participants unintentionally learned sequences of letters generated by an underlying artificial grammar. Participants' implicit and explicit knowledge was assessed immediately after learning and after a retention interval of 1 week. For each time of assessment, participants provided two measures, (a) response times to each letter of the strings, and (b) binary recognition judgments for every string. The crucial finding was that participants' implicit knowledge (measured by RTs) remained stable after the retention interval but their explicit knowledge (measured by yes-no recognition judgments) significantly decreased.

There is one key aspect of the findings that deserves critical investigation. Tunney's empirical evidence was based on the assumption that in his task recognition scores reflect explicit, rather than implicit, knowledge of the items encountered in the initial learning phase. As Tunney points out himself, it is quite conceivable, however, that participants' recognition scores might have been based, for instance, on the fluency of their responding to strings they had to judge; and that the fluency of responding was determined, at least in part, by implicit knowledge. Thus, participants' recognition scores might have reflected both implicit and explicit knowledge of items encountered in the learning phase. The first experiment of this dissertation was designed to address this issue while at the same time attempting to keep intact relevant features of the experimental manipulation which make it valuable. The first experiment constitutes a replication of Tunney (2003) with the difference that confidence ratings for every recognition judgment were required. The rationale of introducing confidence ratings is that they may help to separate implicit from explicit influences on simple binary recognition judgments. Therefore, the only differences to the original study were: (1) the introduction of confidence ratings after every recognition judgment, and (2) the exclusion of the control group exposed to random strings.

In Experiment 2, I asked whether repetitions of the same items might be the source of the dissociation originally observed by Tunney (2003). The main difference between Experiment 1 and Experiment 2 is that in Experiment 2 repetition of items across tests were excluded. As mentioned above, Tunney had used exactly the same strings twice at each time of testing. Because a close examination of the recognition scores at the initial and the 1-week assessments indicates that the observed decline in d's was almost exclusively carried by an increase in false alarm rates, it appears possible that the repetition of test items might have been at least partly responsible for Tunney's (2003) observed decline in recognition rate over the 1-week period. More specifically, it is conceivable that participants when they were repeatedly tested on the same incorrect items might have (correctly) remembered that they had seen the (incorrect) items previously but might have committed a *source confusion* error. The source confusion would have increased the false alarm rate which, in turn, would have caused a decline of the d'. Therefore, in Experiment 2, I address this issue by avoiding repetition of the same items across tests.

In Experiment 3, I investigated whether inference may be the in the background of the pattern of results observed in the previous Experiments 1 and 2. In this case an interference task was introduced instead of the retention interval. It was predicted that if interference plays a role dissociating the forgetting patterns of implicit and explicit knowledge, then the results of Experiment 3 should be similar to the results of Experiments 1 and 2.

In Experiment 4A, I attempted to extend the findings obtained with the artificial grammar paradigm to the SRT task. The underlying rationale was that if the single-system model proposed by Shanks et al. (2003) is based on empirical results obtained with this task, then a better test for the model should be based on the same experimental paradigm.

In Experiment 4B, I increased the retention interval up to 100 days. The key question here is whether a longer retention interval induces an observable decrement in the implicit knowledge measure. Data collected in this experiment are useful to compare the mathematical functions in the forgetting rates of implicit and explicit knowledge with 3 data points (1 day, 7 days, and 100 days).

Finally, I ask whether the single-system model of Shanks et al (2003) my be able to simulate the qualitative pattern of results of Experiments 1, 2, and 3; and particularly, the quantitative dissociations between implicit and explicit knowledge of the empirical data from Experiments 4A and 4B. On the whole, the simulations show that adjustments of the parameters related to error terms are necessary to simulate the empirical data. Interestingly, modifications of the parameter related to memory strength alone cannot adequately reproduce the pattern of empirical results.

4.1 Experiment 1: Replication of Tunney (2003)

Previous research (e.g., Nissen et al. 1989; Willingham & Dumas, 1997) has shown that priming can be retained over relatively long periods of time. The data reported by Tunney (2003), are the first to clearly show that recognition of the same information, shows a very different pattern of forgetting. In this sense, this data support the view that at least some forms of implicit knowledge can be retained for longer periods than explicit knowledge and thus may be mediated by a different system.

The first experiment is an attempt to replicate and assess how robust is the key finding that explicit knowledge decreases after 1 week but implicit knowledge is preserved (Tunney 2003). Participants incidentally learned a set of letter-strings generated by an underlying implicit grammar; that is, they were *not* instructed to deliberately attempt to recall or memorize the strings, but they were simply required to type as rapidly and accurately as possible each single letter from the grammatical strings. Implicit and explicit tests were conducted immediately after the learning phase and after a retention interval of 1 week. The implicit test resembled the learning phase in that participants had to type on the keyboard a key matching a letter presented on a computer's screen, but the letters corresponded to old and new sequences of letters. The difference in reaction time for letters of new and old strings served as an estimate of implicit knowledge. After participants typed each string, the explicit measures were collected in two steps, (1) participants provided a binary (new-old) recognition judgments for each string, and (2) rated in a 3-point scale how confident they were of each recognition judgment.

The only relevant difference between the replication and the original experiment resides in the fact that participants had to provide confidence ratings after every recognition judgment. The introduction of confidence ratings has at least 3 important advantages. First, because confidence ratings are required in a second step after every recognition judgment, it is unlikely that this modification may affect the replicability of the original findings.

Second, confidence ratings enable a more fine-grained measurement of recognition because instead of providing only binary (new/old) recognition responses, participants also provide a confidence rating on a 3-point scale. As explained in the introduction (p. 25) the confidence ratings may contain important complementary information about the subjective criteria that determine participants' performance on explicit tests.

Third, the behavior of the two measures may be compared before and after the retention interval to estimate whether recognition and confidence tap the same knowledge base and whether this knowledge is measured with the same sensitivity with both methods. On the one hand, if both recognition and confidence show an equivalent loss, then one can conclude that both tests probably tap the same knowledge base and that this knowledge is measured with approximately the same sensitivity with both methods. On the other hand, if recognition and confidence dissociate, then one can conclude that the measure showing a decrease after a retention interval is more sensitive to variations in knowledge strength than the measure not showing a decrease. The latter conclusion may be warranted by the reasonable assumption that the passage of time reduces knowledge strength; therefore, the one measure capable of detecting the reduction is plausibly assumed to be more sensitive.

Additionally, the replication has the following minor differences relative to the original study. First, I only ran the experimental group that was exposed to strings of letters generated by an artificial grammar and not the control group exposed to random strings of letters. Second, I included only a retention interval of 1 week because at this point in time the relevant dissociation between implicit and explicit knowledge was observed. Third, a set of letters in the same row of the keyboard was selected; participants were instructed to keep their fingers on the corresponding keys and to use one finger for every letter to reduce noise in RT responses (cf. Tunney 2003, p. 127). Fourth, a wrong key-press erased the stimulus and presented the next one, whereas in the original study every stimulus remained on the screen until the correct key was pressed. This later change allowed me to collect RT for wrong responses as well.

4.1.1 Method

4.1.1.1 Participants

The participants were 15 undergraduate students from Humboldt University (11 women and 4 men) with ages ranging from 20 to 31. All were naïve to the purpose of the study and were paid 8 Euros for taking part in the 2 experimental sessions.

4.1.1.2 Apparatus

Participants were individually trained and tested in one of five experimental rooms. Each room was equipped with an IBM-compatible PC, a table and a chair. Instructions and stimuli were presented via the computer’s CRT monitor (17 inches) with a resolution of 1280 by 1024 pixel at 85 MHz. Responses consisted of pressing keys on a QWERTZ keyboard and manipulating the computer’s mouse. RT was measured with ExacTicks software and programming was done in Delphi™ 7.0.

4.1.1.3 Materials

Grammatical strings of letters were construed according to a modified version of the artificial grammar used by Brooks and Vokey (1991). I replaced the original surface letters V T X M and R with S D F J and K, respectively. This was done in order to instruct participants to rest their fingers on the same keyboard keys during the entire experiment and, in doing so, minimize the possibility of noise in the RT measure due to searching for the corresponding keys on the keyboard (see Figure 3).

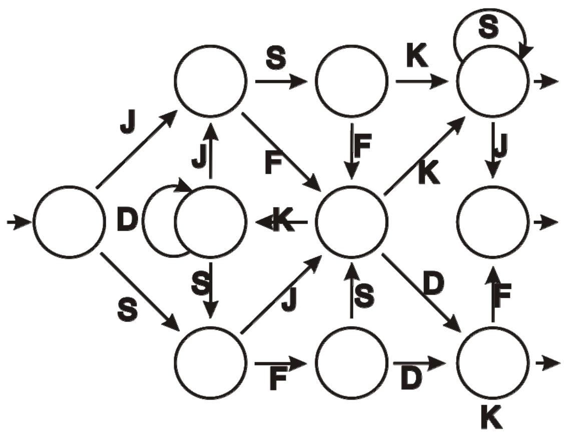

Figure 3: Modified version of the artificial grammar originally used by Brooks & Vokey (1991). Grammatical strings of letters were generated by following the arrows to the terminal positions. Letters are generated along any arrow, with the resulting sequences being grammatical. Ungrammatical sequences were produced by replacing a permissible letter with one that is not permissible in one particular position (see Appendix 1).

Ungrammatical strings were similarly construed by introducing one letter not allowed in a certain position within the string but were of identical length and composed of the same letter-set as the grammatical sequences. Altogether, 32 strings were used, 16 grammatical and 16 ungrammatical (see Appendix 1).

4.1.1.4 Design and Procedure

The procedure closely replicated Tunney (2003). The experiment was completed in two sessions. The first session, about 30 min in duration, was divided into a long learning phase and shorter test phase administered immediately after learning. The second session, conducted 7 days later, involved only a repetition of the test phase. Instructions and prompts were presented on the screen of the computer (in Experiments 1-3 all instructions and written prompts have been translated from German).

Learning phase. Learning involved 5 training blocks. In every block, 16 grammatical strings were presented once in a different randomized order for every participant and for every block. Before and after every string, the word START and END were presented. At these prompts participants had to press the space bar with the thumb. Then, the first target letter of the randomly selected string appeared at the center of the screen and participants had to depress as soon and as accurately as possible the corresponding key in the keyboard. Any response erased the target immediately. If the key pressed did not match the stimulus, then the computer emitted a tone (440 Hz, 85 ms), signaling the mistake. RT was recorded from target onset to key press. The subsequent letter was presented after a response-stimulus interval (RSI) of 200 ms.

Participants were instructed to press keys S, D, and F with the ring, middle and index fingers, respectively, of their left hand and to press keys J and K with the index and middle fingers, respectively, of their right hand (note that these keys are located on the same row of the keyboard). They were also instructed to keep their fingers on the assigned keyboard locations. After every block, participants were allowed to take a break of approximately one minute. Information about the average RT and percentage of hits from the previous block was presented during this time.

Testing phase. Testing involved one measure of RT, one measure of recognition, and one measure of confidence. For RTs, participants were required to respond to each string as they had done in the learning phase by depressing the keys corresponding to the target letters presented on the screen. For measurements of recognition-accuracy, the following question appeared at the center of the screen after every sequence's END prompt: "Do you think this string of letters was…" and below two buttons marked "new" and "old" to which participants were asked to respond with a mouse click. For confidence ratings, the question: "How sure are you?" appeared at the center of the screen after every recognition judgment. Buttons labeled "very sure", "relatively sure", and "guess" were shown horizontally below the question. Participants responded by clicking on one of them.

Closely modeled after Tunney's (2003) experiment, 16 grammatical old strings were presented at test mixed with 16 ungrammatical new strings. The whole test set was presented twice in each session in a random order for every participant. Because the strings used for each test were identical in the 2 sessions, during the second test participants were instructed to try to recognize sequences from the original training phase and not from the previous test phase. Before taking part in the experiment, participants were informed that they would need to return for a second session 7 days later but they were not aware of the experiment's purpose. No feedback of any kind was given during tests.

Figure 4 summarizes the experimental design and the distribution of grammatical and ungrammatical strings for Experiment 1.

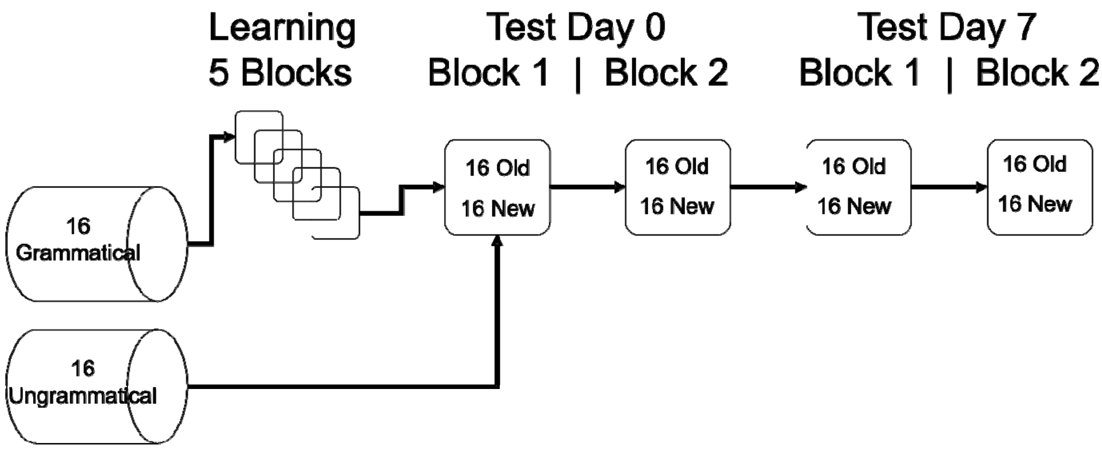

Figure 4: Distribution of grammatical and ungrammatical items used during tests and basic schematic representation of the design of Experiment 1. Note that the same ungrammatical items were used before and after the retention interval, as well as during repetitions of blocks within the same testing day.

4.1.2 Results

In all analyses of this dissertation, a significance criterion of *alpha* = 0.5 was used. For figures displaying within-subject confidence intervals, the method by Loftus and Masson (1994) was used for computations.

4.1.2.1 Learning phase

RTs decreased significantly during the learning phase while error rates were low and constant. An analysis of variance (ANOVA) for RT with block (5 levels) as a within-subject variable revealed a significant effect of block, $F\,(4, 72) = 17.691$, $p < .001$, $MSE = 1{,}721.7$. Error rates ranged from 1% to 3 % and did not change significantly over blocks $F < 1$. It is clear that participants were able to speed up their responses as a consequence of training without an accompanying increase in the error rate.

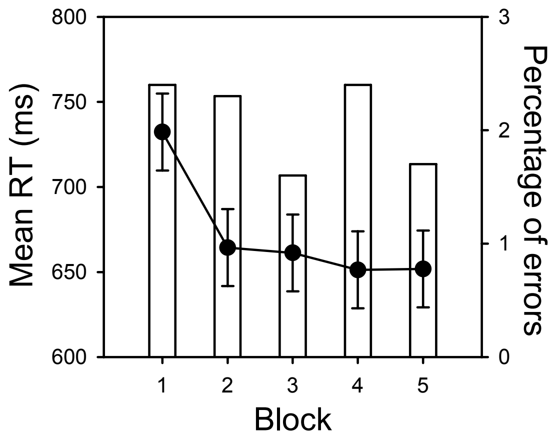

Figure 5: Mean RTs across learning blocks: filled circles, left axis. Mean percentage of errors for the learning phase across blocks, right axis. Errors bars depict within-subject 95% confidence intervals.

4.1.2.2 Tests

I first analyzed the data in much the same manner as described in Tunney's (2003) experiment. Error responses and the first response following an error were not entered into any analyses. Additionally, RTs to the START and END prompts were also excluded. The remaining RTs were averaged for every participant, for every test, and for every type of string (new – old). A priming score was computed by subtracting RTs to old items from RTs to new items. A *t*-test comparing the priming scores for day 0 (24.7) and for day 7 (18.5) showed no effect of time ($t(15)$ = .603, SD = 39.986, p = .556).

For recognition, I used d', the standardized differences of hits minus false alarms according to signal detection theory (Green and Swets, 1966). On those occasions when a hit rate was 1.0 or a false alarm rate was 0, values of 1 - 1/32 or 1/32 (respectively) were used instead (MacMillan and Cleerman, 1991). A *t*-test comparing the mean d's at day 0 (1.02) and at day 7 (.91) showed no effect of time ($t(14)$ = .984 SD = .456 p = .342).

Confidence ratings, the additional measure used in this experimented that had not been included in the original study, were computed for every participant by subtracting the mean ratings for old items from the mean ratings for new items (Shanks and Perruchet, 2002; Shanks, et al., 2003). A *t*-test comparing the mean confidence rating before (1.42) and after (1.06) the delay showed a significant effect ($t(14)$ = 3.314, SD = .416, p = .005). Figure 6 summarizes these findings by displaying the performance on the three measures at both testing times. Additionally, in the bottom panels of the figure the difference scores are presented.

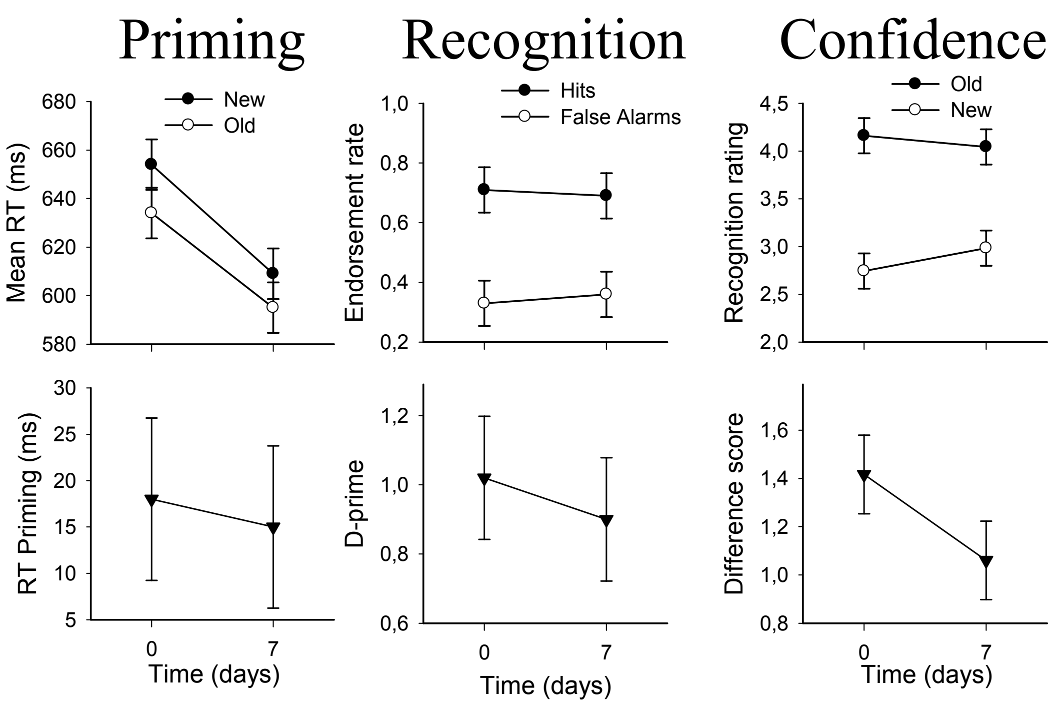

Figure 6: Results for tests conducted immediately after learning and after a delay of 7 days for priming, recognition and confidence. Error bars depict 95% with-subject confidence intervals.

Additionally, I found important to evaluate the role that repetitions of the same items played during the tests. Recall that in the design of this replication (as well as in Tunney's original study), the same targets and lures were repeated in two blocks before and two blocks after the retention interval (see Figure 4). One possibility is that the lures start to be more familiar because they are repeated in every test, thus the participants' ability to distinguish between old and new items may have decreased not only because they forget the targets but also because they misattribute the source of familiarity for the lures; for example, the participants may correctly think that the lures have been previously seen but they may incorrectly believe that the lures were presented in the learning phase. On way to disentangle the effect of repetitions from the effect of memory decay is to split the data collected at the same day into 2 halves. In this way, it is possible to determine whether the ability to distinguish new and old items decreased before the retention interval. Figure 7 summarizes these analyses for RT and recognition.

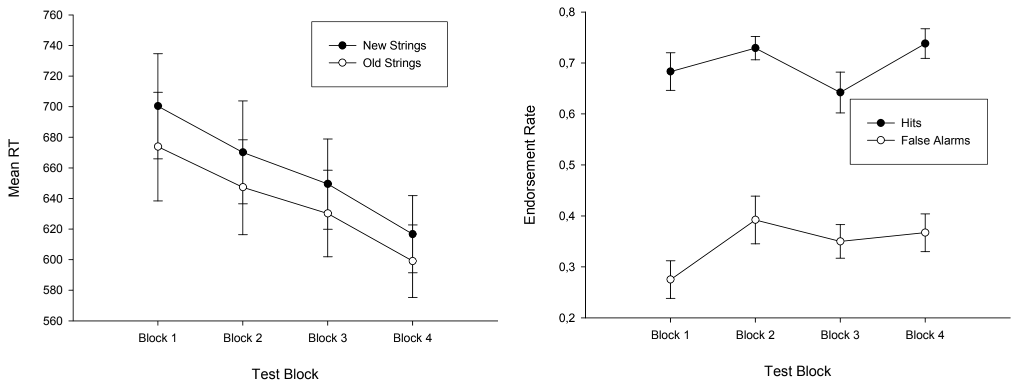

Figure 7: Block analyses for Experiment 1 (replication). Left panel: Mean RTs for new and old strings. Right panel: endorsement rates for old strings (hits) and new strings (false alarms). There is a 1 week time interval between Blocks 3 and 4.

The left panel shows that priming (RT to new items minus RT to old items) remained relatively constant across blocks. However, endorsement rates (namely, recognition), show an increase in the number of false alarms (FA) between Block 1 and Block 2. A *t*-test comparing mean FA rates for Blocks 1 and 2 showed a significant effect of block, ($t(14) = -2.956$, SD = .153, $p = .010$). The same test conducted for hit rates showed no effect ($t(14) = -.991$, SD = .179, $p = .338$).

4.1.3 Discussion

The goal of Experiment 1 was to replicate Tunney's (2003) earlier finding that explicit knowledge in the form of binary recognition judgments decreases after a retention interval of 1 week but implicit knowledge in the form of RT priming is preserved. The only difference between the replication and the original study was that participants provided confidence ratings for every recognition judgment. Additionally, I tested whether repeating the same test items may have selectively interfered with recognition but not with RT priming.

The results showed that neither RT priming nor recognition judgments decreased significantly after the retention interval. However, the confidence ratings did show a significant decrease after the retention interval. Therefore, I replicated the retention of implicit performance as estimated by RT priming, but I failed to replicate the decline in recognition as estimated by d'. Interestingly, I observed a significant decline in explicit knowledge when confidence ratings instead of d's were used to asses recognition performance.

A standard approach to interpret these result would be to assume that (1) confidence ratings and (2) recognition judgments are based on the same information (e.g., Morrell, et al., 2002; Tunney, 2005; Tunney and Shanks, 2003), but that the former constitute a more sensitive measure of explicit knowledge. Under this assumption, one could argue that the observed decrease in confidence ratings conceptually replicates Tunney's finding that explicit knowledge is not preserved after 1 week but implicit knowledge is retained.

However, an alternative approach is to interpret confidence ratings as metacognitive information (e.g., Dienes and Perner, 1999) about the status of recognition judgments. For this, one needs to assume that recognition judgments and confidence ratings do not necessarily tap the same knowledge base (Busey, et al., 2000; Van Zandt, 2000). The present results are not incompatible with this assumption either. In fact, one might ask if recognition judgments held with higher confidence display a different pattern of forgetting than recognition judgments held with lower confidence, but the present data cannot be used to resolve these competing interpretations because an additional effect related to repetitions of the same testing items emerged. In fact, the analysis of repetitions showed clearly that false alarms increased within the same testing day across blocks, specifically in the second and the fourth blocks. Additionally, a *t*-test comparing the proportions of false alarms in Blocks 1 and 2 found a significant effect.

Taking together, the results of the replication emphasize the need to remove the source of noise introduced by including repetitions of blocks with the same items. The most evident finding is that in this experiment, as well as in Tunney's (2003), I observed a lack of the "mirror effect" in recognition performance (Glanzer and Adams, 1985). That is, the ability to recognize old items as old did not proportionally decrease with time as the ability to recognize new items as new did. Specifically, most of the decrease in recognition was due to an increase in the proportion of false alarms but not to a decrease in the number of hits. This finding suggests that repetition of the same items introduces noise into the recognition measure. This does not constitute conclusive evidence that the original finding is replicable and robust unless the potential source of noise is removed. This step is taken in the next experiment.

4.2 Experiment 2: The role of repetitions

Experiment 1 did not show clearly the role played by the repetition of items. More specifically, it is conceivable that participants, when they were repeatedly tested on the same lures, might have (correctly) remembered that they had seen the lures previously but might have committed a source confusion error (e.g., Johnson, et al., 1993). In other words, items that were not presented during the learning phase might become more familiar due to the fact that they are repeated in every test. Accordingly, the source confusion would have increased the false alarm rate which, in turn, would have introduced noise to the explicit measure estimated by d'. For this reason, the goal of Experiment 2 was to control for item repetitions across tests.

The second goal of Experiment 2 was to test if the recognition measure comprises indeed an explicit measure of memory. Recall that Tunney's (2003) dissociation argument is based on the assumption that in his task recognition scores reflect explicit, rather than implicit, knowledge of the learned items. It is quite conceivable, however, that participants' recognition performance may be based, for instance, on their fluency of responding to the strings, and that fluency may be determined, at least in part, by implicit knowledge. Thus, participants' recognition performance may reflect both implicit and explicit knowledge of the items encountered in the learning phase. To address this issue, I suggest to apply a somewhat different method to analyze the data from confidence ratings: namely to compute separate d' values for (a) items to which participants respond that they are sure and (b) items to which they respond that they only guess. With this method, one may estimate the contribution of implicit and explicit information to the overall recognition performance. Accordingly, performance on (a) items more likely represents explicit knowledge whereas performance on (b) items more likely represents implicit performance. One key prediction would be that if explicit knowledge declines but implicit knowledge remains constant, then performance on (a) items should decrease but performance on (b) items should remain relatively constant.

In all other aspects Experiment 2 was a conceptual replication of Experiment 1. As in Experiment 1, participants were exposed to 16 grammatical strings in a learning phase. Implicit and explicit measures of learning were assessed both immediately upon completion of the learning phase and again after a 1-week retention period. In addition, after typing in their binary recognition scores, participants were asked to indicate the confidence of their recognition decision on a 3-point scale. In contrast to Tunney (2003), participants in Experiment 2 received half of Tunney's original test items in a single block for the first test phase. After the retention interval of 1 week, they were presented with the remaining test items in a single block (see Appendix 2 for more details on the effect of item reduction on the measurements' statistical power). Figure 8 schematically summarizes the main characteristics of Experiment 2.

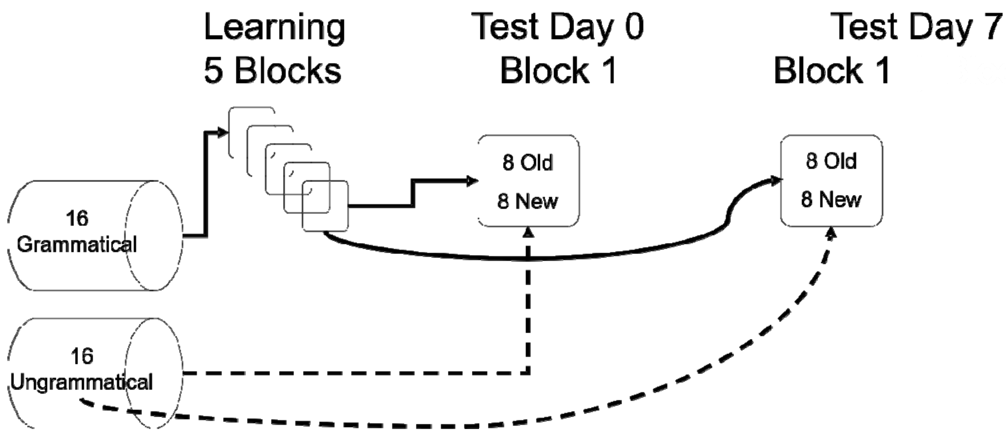

Figure 8: Design for Experiment 2: No repetitions. Note that neither the grammatical items nor the ungrammatical ones were presented twice on Day 0 and 7.

In addition to the two issues described (use of non-overlapping test items and assessment of confidence ratings), Experiment 2 differed from Tunney's original study in the same minor details as the previous Experiment 1. First, I ran only the experimental group that learned grammatical strings and not the control group. Second, I did not include Tunney's 2-weeks retention interval because it did not show relevant changes.

4.2.1 Method

The apparatus, learning, and testing phases were identical to Experiment 1 except in the particulars described above.

4.2.1.1 Participants

Participants were 14 female and 6 male undergraduate students at Humboldt University, Berlin, who received 8 Euros in exchange for taking part in the experiment. Ages ranged from 18 to 25. All were naive to the purpose of the study. One participant was removed from all analyses because she rated all items of both tests sessions as "old".

4.2.1.2 Procedure

The items used in the test phases differed from the ones used in the original experiment by Tunney (2003). For every participant, a different subset of 16 new and 16 old items was randomly determined. Half of the items were presented, in random order, during the first test. The remaining items were presented in a random order during the second test. Consequently, there were four different sets of items randomly selected for every participant depending on its grammaticality and test-phase: (a) 8 ungrammatical items used for the first test, (b) 8 grammatical items used for the first test, (c) 8 ungrammatical items used for the second test, and (d) 8 grammatical items used for the second test. Importantly, none of the item sets overlapped. Therefore, every participant made 16 new-old judgments in each test phase (in contrast to 64 judgments in Tunney's original experiment. See Appendix 2).

4.2.2 Results

4.2.2.1 Learning Phase

Error rates and RTs were determined separately for every participant and every block. Errors ranged from 2% to 3%, and did not significantly change over blocks, $\underline{F} < 1$. In contrast, RTs decreased significantly during the learning phase. An ANOVA for the RTs with block (5 levels) as a within-subjects variable, revealed a significant main effect of block, $F(4, 72) = 17.69$, MSE = 1,721, $p < .001$. Thus, participants were able to speed up their responses as a consequence of training without increasing their error rates.

4.2.2.2 Test Phases

First, RTs to individual letters of strings presented in the test phases were averaged separately for every participant, every test phase, and every type of string (new vs. old). The resulting mean RTs are displayed in Figure 9. As can be seen, RTs to old items were faster than RTs to new items at both times of testing.

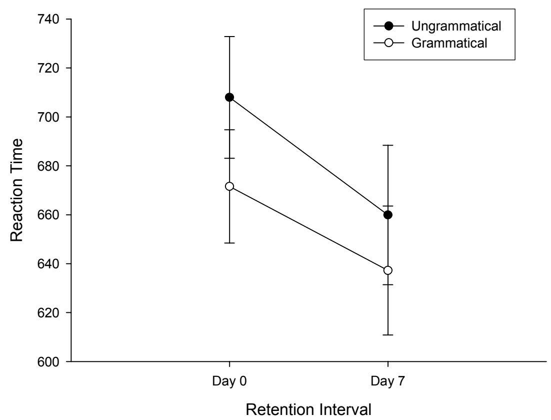

Figure 9: Mean reaction times for grammatical (old) and ungrammatical (new) test strings in Experiment 2. Error bars depict standard errors of the mean.

A 2 (time of testing: pre vs. post) X 2 (type of string: new vs. old) repeated measures ANOVA revealed a significant main effect of time of testing, $F(1, 18) = 5.72$, MSe = 5636.37, $p < .05$, and a significant main effect of type of string, $F(1, 18) = 11.02$, MSe = 1503.31, $p < .01$, but no significant interaction between time of testing and type of string, $F(1, 18) < 1$. These results indicate that the RT advantage for old over new items did not change with time. Thus, the implicit knowledge measure was not affected by the retention interval. This particular finding replicates the results described by Tunney (2003) and obtained in Experiment 1.

Figure 10 depicts the mean endorsement rates for old (hits) and new (false alarms) items at the two times of testing. Importantly, both the ability to recognize old items as old and the ability to recognize new items as new decreased proportionally with time.

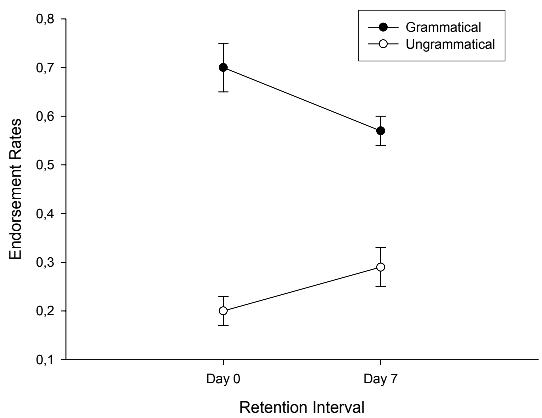

Figure 10: Endorsement rates for grammatical (old) and ungrammatical (new) test strings in Experiment 2. Error bars depict standard errors of the mean.

A corresponding 2 (time of testing: pre vs. post) X 2 (type of string: new vs. old) repeated measures ANOVA on endorsement rates revealed a significant main effect of type of string, $F(1, 18) = 106.7$, MSe = 0.027, $p < .01$, and a significant interaction between time of testing and type of string, $F(1, 18) = 5.81$, MSe = 0.0349, $p <. 05$. The main effect of time of testing was not significant, $p > .30$. A direct comparison of participants' d's at pre and post revealed a significant effect of time of testing, $F(1, 18) = 6.06$, MSe = 0.819, $p < .05$, indicating that recognition performance was affected by the 1-week retention interval.

4.2.3 Discussion

Taken together, these findings replicate the empirical dissociation reported by Tunney (2003). The implicit measure of knowledge (i.e., difference in RT for old and new items) was not affected by a 1-week retention interval while the explicit measure of knowledge (recognition) was affected. The dissociation was observed although the items used in the testing phases were different at the pre and post times of assessment. Thus, the repetition of test items in the original Tunney experiment did not cause the dissociation.

One might argue, of course, that the lack of effect for the implicit measure of knowledge might have been due to a lack of statistical power for that measure. Although such a lack-of-power argument is always very difficult to refute in the absolute, there are at least 3 good reasons that speak against the lack-of-power argument. First, the decline in RT priming was very small (14 ms) and was comparable in size to the standard errors observed at Days 0 and 7. In contrast, the decline in d's was much larger and was about 4-5 times the size of the respective standard errors.

Second, Experiment 2 is a replication of Tunney (2003). That is, the empirically observed dissociation in the time-pattern of implicit and explicit knowledge has been observed in at least two independent studies thus far; the obtained pattern is not unique to this experiment.

Third and perhaps even more convincing, in order to address this issue, I computed a dRT score that is analogous to d's used as measure of recognition (Poldrack & Logan, 1997). According to Poldrack and Logan:

$$dRT = \frac{M_{new} - M_{old}}{(SD_{old}/2 + SD_{new}/2)}, \qquad (1)$$

where *dRT* is the degree of discriminability for RTs (analogous to d'), *M*s are the mean RTs, and *SD*s are the standard deviations for RTs. The resulting dRT scores were .07 (SE = .04) for the first test and .09 (SE = .05) for the second test. The scores did not differ for the two times of testing, $\underline{F} < 1$. Importantly, thus, even with the dRT measure, there still was no significant decline on RT priming over the 1-week retention interval.

Experiment 2 also aimed to assess whether recognition can be considered a measure of explicit, rather than implicit knowledge. To address this issue, participants were required to provide confidence ratings for each recognition judgments on a 3-point scale. The confidence ratings allow to separately compute d's for (a) items for which participants were sure, and for (b) items for which participants were only guessing. The rationale was that if recognition measures explicit knowledge, then the d's for case (a) should show a similar time trajectory as the overall d's. In addition, d's for case (b) should not be significantly different from zero and should not differ for the two times of assessment.

Therefore, d' scores were separately computed for cases (a – "very sure" and "relatively sure") and (b – "guess"). The d's for case (a) were 2.07 at the pre and 0.97 at the post time of assessment. The d's were significantly different from zero at the pre and post times of testing, $F(1, 18) = 108.74$, MSe = 0.749, $p < .01$, and $F(1, 18) = 25.84$, MSe = 0.695, $p < .01$, for the pre and post testing, respectively. In addition, the d's differed for the two times of testing, $F(1, 18) = 14.46$, MSe = 0.793, $p < .01$, thus imitating the overall findings.

In contrast, the d's for case (b) were -0.16 at the pre and -0.22 at the post time of assessment. The d's were not significantly different from zero at the pre and post times of testing, both *F*'s < 1. Even more importantly, the d's did not differ for the two times of testing, $F < 1$. Given these results, it appears that the overall recognition findings were carried primarily by scores that were accompanied by high confidence ratings. Thus, the recognition measure used here and in Tunney (2003) appears to assess primarily explicit and not implicit knowledge.

Taken together, these results suggest that the dissociation reported by Tunney is robust. It is neither an artifact of the items' repetition nor affected by contamination of the implicit knowledge on the explicit measure.

4.3 Experiment 3: Interference

While the goal of Experiment 2 was to conceptually replicate the main results of Tunney (2003), albeit with two major methodological improvements, the primary goal of Experiment 3 was to test if the specific pattern of results obtained in Experiment 2 might be due to interference. Why implicit and explicit knowledge show different forgetting patterns? According to Tunney (2003), the pattern of endorsement rates might indicate that *interference* is the cause of apparent decay of recognition. However, the author does not indicate what precisely is meant by interference and how this hypothesis is linked to other research bodies. In Experiment 3, I address this issue in detail by providing a brief overview of converging evidence that points to a crucial role of interference in forgetting. First, I will frame the concept of interference in the context of classic research conducted primarily with paired-associated procedures. Second, I will illustrate a related concept *consolidation*, that is also crucial for understanding the functioning of interference and its role in forgetting. Third, I will summarize recent evidence from sleep research showing that diverse forms of knowledge are differently enhanced (consolidated) by slow wave sleep (SWS) and rapid eye movement (REM) sleep. Finally, given that (1) different forms of knowledge apparently show divergent consolidation patterns, and that (2) interference is regarded as the process that hinders memory consolidation, I will hypothesize that interference may play a different role for the retention of implicit and implicit knowledge.

It has been traditionally thought that there are three different mechanisms that induce forgetting over long retention intervals. The first mechanism is spontaneous *decay* of memories, presumably due to physiological and metabolic processes that cause progressive degradation of the synaptic changes in the brain. The second mechanism is *interference*, the disruptive effect occasioned by learning of new materials. And the third mechanism is a *retrieval* failure due to response competition (e.g., cue-overload) or errors in memory search (e.g., Shiffrin, 1970). Accounts based on decay and interference share in common the assumption that forgetting is due to a reduction in memory strength over the retention interval. On the other hand, accounts based on a retrieval-failure mechanism (e.g., Watkins and Watkins, 1975) emphasize the idea that items may indefinitely be kept in memory but become less accessible with time. In turn, decay differs from interference in that the first is supposed to occur to memory traces that have been successfully encoded in memory, while interference most probably degrades (but not necessarily overwrites) previously established traces that have not yet had a chance to consolidate.

Interference theories of forgetting are currently gaining revived interest. On one side, explanations based solely on decay processes have been partially abandoned (for an exception see e.g. Altmann and Gray, 2002), because research on long-term memory tends to favor multi-causal explanations (e.g., Cowan, et al.,

2001) due to the fact that it is experimentally difficult to rule out alternative mechanisms such as interference. On the other side, explanations based on a lack of accessibility do not compete with interference theories because they merely stress an additional mechanism that, although proven to be strong in the laboratory, presumably does not play a decisive role in daily life (Wixted, 2004). For these reasons, I will explore in Experiment 3 more extensively the ability of interference mechanisms to account for possible dissociations in forgetting rates of implicit and explicit knowledge.

The study of interference dominated research on memory until the 50's (Bower, 2000). Most of the studies were concerned with retroactive and proactive interference in new learning situations. The standard paradigm for research of these phenomena was the paired-associate task in which participants initially learn two lists of pairs (A-B, A being, for example, names of cities and B names of animals). During the next phase, participants learn a second set of responses related to the first list (A-C). Retroactive interference (RI) is demonstrated when recall of the first list is substantially impaired in comparison to a control group not exposed to the A-C list.

One current review of these classical studies (Wixted, 2004), informed by recent advances in neuroscience and psychopharmacology, suggests an important role for retroactive interference in forgetting. Apparently, consolidation - the processes associated with the formation of new knowledge (Dudai, 2004; Müller and Pilzecker, 1900) - seems to interfere retroactively with previously formed information that is still undergoing the process of consolidation (McGaugh, 2000). For example, there is clear evidence that amnesia induced by alcohol consumption paradoxically plays a facilitative role on the consolidation of learning that occurred before the alcohol intake. This apparently happens because alcohol prevents the formation of new memories that would otherwise cause retroactive interference (Mueller, et al., 1983). Indeed, the bulk of current evidence seems to suggest that the interplay between memory consolidation, natural degradation of memory strength, and interference originated in unspecific new learning situations may account for the process of forgetting in general.

More interesting for understanding the dissociation between implicit and explicit knowledge in forgetting is the fact that consolidation of different forms of memory is correlated with different sleep states (Plihal, 1997; Plihal and Born, 2000). Declarative memory benefits from long-wave sleep whereas motor skills seem to better consolidate after phases of REM sleep (Gais and Born, 2004). Furthermore, there is evidence that sleep may facilitate the formation of explicit knowledge. This is, implicit learning of sequences in a SRT task promotes later explicit knowledge in a generation task when participants have slept but not when participants stay awake (Born and Wagner, 2004; Fischer, et al., 2006; Walker and Stickgold, 2004).

Additionally, it has been demonstrated that awareness is an important factor for the consolidation of motor skills during sleep. When motor skills are consciously (explicitly) acquired they only improve after a retention interval including sleep. But, when motor skills are implicitly acquired, the improvement is observed both after awake and after sleep intervals (Robertson, et al., 2004). This pattern of results seems to suggest that consolidation and interference processes may have dissimilar effects on different forms of knowledge. This is so because if sleep differentially supports consolidation of different forms of memory, then it seems also possible that interference differentially disrupts different forms of knowledge consolidation.

In this dissertation, I am interested in formulating a specific mechanism that may account for the dissociation in the retention rates of implicit and explicit memory. Such an hypothesized mechanism may consist of *retroactive interference* produced by any experience that differentially hinders the consolidation process of implicit and explicit knowledge.

At the present time, I have indirect theoretical and empirical evidence to hypothesize a more detailed mechanism. Despite the fact that it is not clear whether interference processes may also be related to the conversion process of already accessed memories at the time of retrieval (Blank, 2005) or the prevention of knowledge consolidation as explained above, research on forgetting, interference and consolidation draws some pertinent constraints for this hypothetical mechanism. First, the interference episode does not need to be especially incompatible with the learned material. Apparently, as explained above, simple everyday mental exertion produces an interference effect. Second, there are differential facilitation effects of sleep on declarative and explicit memory, on the one hand, and motor skills, on the other hand, which may also indicate differential disruption effects of interference. According to the findings in sleep research, this hypothesis should also assume that interference is less effective on already consolidated knowledge. Thus, this kind of interference can be differentiated from other obtrusive processes that might occur during the encoding or retrieval of the learned material (e.g., Anderson, et al., 1994).

One final point concerns how to methodologically distinguish between decay and interference. As explained above, decay is defined as a loss of stored information with the simple passage of time. Therefore, I reasoned that the most straightforward way to rule out decay is to simply remove the retention interval between tests and replace it with an interference task. In this manner, a reduction in memory performance may only be attributed to interference. In experiments where a retention interval is incorporated there is no way to disentangle the joint contribution of decay and interference.

To summarize, previous research on the effects of REM sleep has shown differential effects on the consolidation of implicit and explicit knowledge. Furthermore, it has been observed that some components of implicit knowledge may be conceived as motor programs (Ans, Coiton, Gilhodes, & Velay, 1994; Tubau & Lopez-Moliner, 2004); thus, if interference is not targeted to be especially incompatible with already learned motor skills, there is no reason to expect that interference would affect the expression of implicit knowledge. Therefore, this form of interference should degrade only explicit knowledge.

When may interference more successfully reduce explicit knowledge? Theoretically, the closer the interference to the learning experience, the greater should be the effect in a subsequent test. This is so because if knowledge requires a consolidation time, then it should be more susceptible to be interfered during this consolidation phase.

Why would interference affect forgetting of implicit and explicit knowledge in the specific task used here and in Tunney (2003) in the first place? If it is assumed, for instance, that learning in the artificial grammar learning task consists, at least in part, of acquiring associations between consecutively typed manual responses, then any newly typed sequences of manual responses that do not correspond to the artificial grammar will weaken -absolutely and/or relative to other representations- the strengths of the acquired associations. In the real world, this interference might be due to the typing of any text on a typewriter or computer, for instance, to playing a piano, and the like.

Experiment 3 was similar to Experiment 1 and Experiment 2. Again, a learning phase was followed by two test phases. In this case, however, the two test phases were not separated by a 1-week retention interval but by an interference task. In the interference task, participants responded to a series of random strings of letters similar to those of the learning phase. Figure 11 illustrates the basic design of Experiment 3.

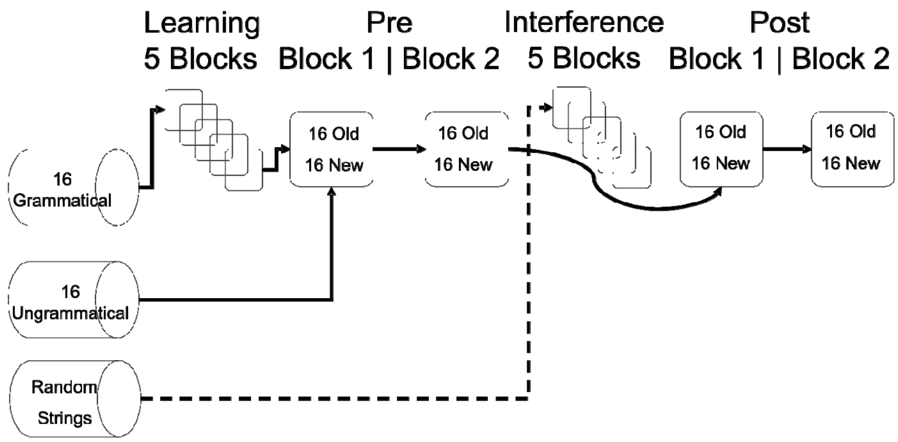

Figure 11: Design and distribution of grammatical and ungrammatical strings for Experiment 3: Interference. Note that the only change relative to Experiment 1 is the introduction of 5 random blocks between pre and post times of testing.

If indeed the empirical dissociation in forgetting of implicit and explicit knowledge that we observed in Experiment 2 is due to different sensitivities to interference rather than decay, then we should obtain a pattern of results that closely mirrors the dissociation pattern observed in Experiment 2. If, on the other hand, the obtained dissociation is caused by differences in decay rates, then the results of Experiment 3 should not be comparable to the findings obtained in Experiment 2.

4.3.1 Method

4.3.1.1 Participants

Participants were 16 undergraduates at Humboldt-University, Berlin (11 women and 5 men) with ages ranging from 20 to 28. All were naive to the purpose of the study and received credit for taking part in the experiment. Again, one participant had to be excluded from the analyses because she classified all items of the test phase as “old”.

4.3.1.2 Materials

The materials used in the learning phase were identical to those used in Experiment 1. In the testing phase, the original items from Tunney (2003) were used (including the block repetition) rather than the test items from Experiment 2, to optimize the comparison to Tunney's data.

The items used in the *interference phase* were randomly generated strings composed of the letters S, D, F, J, and K. All letters had an equal probability (.2) of occurrence in each interference trial. The lengths of the interference strings varied randomly between 3 and 7 letters. For every participant, 5 blocks of 16 strings were presented in the interference phase.

4.3.1.3 Procedure

The learning and test phases were conducted in the same manner as in Experiment 1 but in a single session of approximately 40 minutes. The first test phase was conducted immediately following the learning phase and was followed by the interference phase. The second test was conducted after the interference phase. The interference phase, except for the use of randomly generated strings as described above, closely resembled the learning phase. All instructions, prompts, feedback, blocks, and breaks between blocks used in the learning phase, were also used in the interference phase.

4.3.2 Results and Discussion

Data were analyzed and aggregated in the same manner as in Experiments 1 and 2.

4.3.2.1 Learning Phase

Error rates ranged from 1% to 3%, and did not significantly change over blocks, $F < 1$. In contrast, RTs decreased significantly during the learning phase. An ANOVA on RT with block (5 levels) as a within-subjects variable, revealed a significant main effect of block, $F(4, 56) = 9.12$, MSe = 1,911.3, $p < .001$. Clearly, participants were able to speed up their responses as a consequence of training without increasing the percentage of errors.

4.3.2.2 Test Phases

The resulting mean RTs are displayed in Figure 12. As can be seen, response times to old items were faster than response times to new items at both testing times.

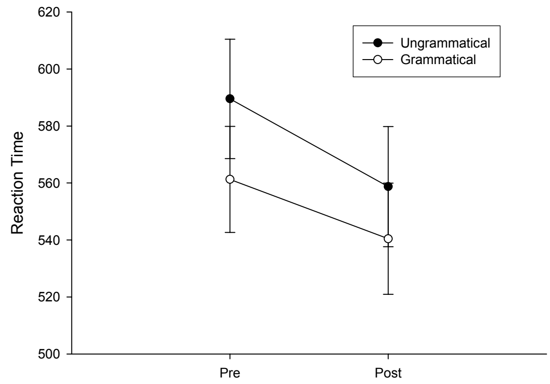

Figure 12: Mean reaction times for ungrammatical (new) and grammatical (old) test strings in Experiment 3. Error bars depict standard error of the mean.

A 2 (time of testing: pre interference vs. post interference) X 2 (type of string: new vs. old) repeated measures ANOVA revealed a significant main effect of time of testing, $F(1, 14) = 10.22$, MSe = 977.37, $p < .01$, and a significant main effect of type of string, $F(1, 14) = 16.27$, MSe = 499.92, $p < .01$, but no significant interaction between time of testing and type of string, $p > .26$. These results indicate that RT priming (implicit knowledge measure) did not change as a result of interference.

Figure 13 contains the mean endorsement rates for old and new items at the two times of testing. Close inspection of this figure shows that the endorsement rates for old items were higher than the endorsement rates for new items, both before and after the interference phase. More importantly, the mean d' decreased from the first (1.04) to the second (.72) time of testing.

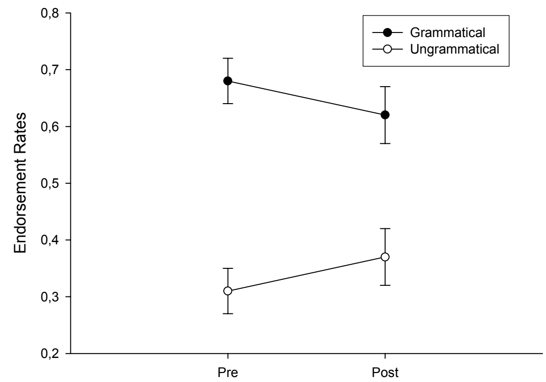

Figure 13: Mean endorsement rates for grammatical and ungrammatical test strings in Experiment 3. Error bars depict standard errors of the mean.

A corresponding 2 (time of testing: pre interference vs. post interference) X 2 (type of string: new vs. old) repeated measures ANOVA on participants' endorsement rates revealed a significant main effect of type of string, $F(1, 14) = 72.87$, MSe = 0.02, $p < .01$, and a significant interaction between time of testing and type of string, $F(1, 14) = 5.02$, MSe = 0.01, $p <. 05$. The main effect of time of testing was not significant, $p > .91$. A direct comparison of participants' d's before and after the interference phase revealed a marginally significant effect of time of testing, $F(1, 14) = 3.82$, MSe = 0.208, $p < .08$, indicating that recognition was indeed affected by interference.

Taken together, these findings replicate the empirical dissociation observed by Tunney (2003) and in Experiment 2 in a novel interference paradigm. The implicit measure of knowledge (RT priming) was not affected by interference while the explicit measure of knowledge (d') was. These, results do not, by themselves, resolve the theoretical debate between single-system and multiple-systems theories of implicit and explicit knowledge. However, the findings add an important empirical constraint to the existing literature because the simplest and most stringent version of the single-system view predicts that interference decreases the strengths of memory representations, and the strengths of memory representations determine both their implicit and explicit accessibility to the same extent (e.g., Perruchet, Bigand & Benoit-Gonin, 1997; Perruchet & Vinter, 2002). In its most simple version, the single-system view would not predict that interference would lead to different forgetting rates for explicit and implicit knowledge. Thus, the results of Experiment 3 make clear that the simplest forms of single-system theory cannot be correct because they cannot explain the present results. Whether the parameters that need to be included in a single-system theory to explain the present dissociation in forgetting rates for implicit and explicit knowledge (e.g., different thresholds for explicit and implicit accessibility) are warranted is a question that is addressed in Experiments 4A, 4B and in the Simulations.

4.4 Experiment 4A: Forgetting in a serial reaction time (SRT) task

The previous Experiments 1-3 have shown that implicit and explicit knowledge about artificial grammars may display different forgetting patterns and may be differently affected by interference. An additional question is whether this pattern of results is also observed in other tasks. In Experiment 4, I attempt to replicate (by using one retention interval) and extend (by using two retention intervals) the empirical data of Shanks et. al. (2003, Experiment 3). There are at least two important reasons to attempt an extrapolation of the artificial grammar findings to the serial reaction time (SRT) task. First, research on implicit learning and implicit memory has made it clear that evidence based on a single experimental paradigm may not be sufficient to warrant the acceptance of single or multiple-system perspectives.

Second, one of the most detailed single-system models of memory and learning is based on data obtained with a SRT task (Shanks, et al., 2003). Therefore, the next logical step is to establish the generality of the previous findings with this alternative experimental paradigm that is widely used on implicit learning research.

In a typical SRT task participants are presented with a sequence of stimuli, for example an 'X' at one of four different locations on a computer screen, and must perform a motor response to each stimulus, for example with a button press mapped onto each location of the 'X'. The successive locations of the stimuli are typically determined by second order conditional (SOC) transitions underlying the sequence. Participants' knowledge of the sequential transitions is revealed through progressive reductions in the reaction times (RTs) of the motor responses that correctly match the stimuli presented on the screen.

One of the practical difficulties in attempting to extrapolate previous findings of Experiments 1-3 to the SRT task is that Shanks et al. (2003) used both deterministic (Experiments 1 and 2) and probabilistic sequences (Experiment 3). However, their computational model is based solely on participants' knowledge of probabilistic sequences assessed once after the learning phase. The use of probabilistic sequences was convenient in Shanks' experiment because explicit information about the sequence is lower in probabilistic than in deterministic tasks (especially in those with no RSI). Nevertheless, the goal of the present research is to obtain a base line of explicit knowledge that is strong enough to allow for the possibility of observing forgetting of explicit memory. Therefore, the main methodological difference between the experiment reported here and the Experiment 3 of Shanks et al. (2003) is that I used (1) a deterministic sequence for training participants, and (2) conducted assessments of implicit and explicit knowledge at two different retention intervals. In fact, there is evidence that deterministic sequences provide a greater chance to increase recognition scores (e.g. Destrebecqz and

Cleeremans, 2001). All other features of Shanks et al. Experiment 3 are replicated including the use of a RSI of 250 milliseconds in order to maximize the likelihood of the sequence being learned explicitly.

4.4.1 Method

4.4.1.1 Participants

Fifty undergraduate students (18 men and 32 women) from the Konrad Lorenz Foundation (Bogotá, Colombia) were recruited to take part in this experiment. They received course credit for participating. All were naïve with regard to the topic and goals of the experiment.

4.4.1.2 Apparatus

Similar to the stimulus presentation in Experiments 1-3, RT measurement, and response recording were all implemented on IBM-compatible PCs with 33-cm color monitors and QWERTY keyboards. Four boxes were presented horizontally at the center of the computer's screen in white against a gray background. The boxes had 13 mm wide and 13 mm high. On each trial, a black X appeared in the center of one of the boxes. The boxes are from now on referred to as Locations 1-4 from left to right.

Closely modeled after Shanks et al. (2003), two second order sequences (SOC1 = 3-1-4-3-2-4-2-1-3-4-1, SOC2 = 4-3-1-2-4-1-3-2-1-4-2-3) were used. These sequences were equated with respect to location frequency (each location occurred three times), first-order transition frequency (each location was preceded once by each of the other three locations), reversals (each sequence had one reversal e.g., 2-4-2), and repetitions (no repetitions in either sequence). The only difference between the two sequences was in their second-order and higher order conditional structure.

4.4.1.3 Procedure

The experiment comprised 12 training blocks during which participants were exposed to a four-choice SRT task. Each block consisted of 100 trials, for a total of 1.200 trials. On each trial, participants reacted to the location of the target as quickly as possible by pressing the corresponding key. Keys V, B, N, and M corresponded to Locations 1-4, respectively. Participants were required to respond to locations 1 and 2 with the middle and index fingers, respectively, of their left hand, and to locations 3 and 4 with the index and middle finger, respectively, of their right hand. Participants were instructed to respond to the targets as fast and as accurately as possible (in Experiment 4 all instructions and written prompts have been translated from Spanish). Each block of target location trials began at a random point in the sequence. At the end of each block, participants were informed about their average RT and percentage of errors in the block. A target location trial ended when a participant pressed the correct key, at which time the target was erased. Response latencies were measured from the onset of the target to the completion of a correct response, and errors were recorded. The next target appeared after a 250-ms RSI interval. Errors were signaled to participants by a beep. For counterbalancing purposes, about half of the participants were trained on the SOC1 sequence and the remainder on the SOC2 sequence.

Tests: the same tests were conducted (1) immediately after the learning phase and (2) after 7 days. All tests involved a recognition judgment for chunks from the old (trained) sequence and from the new (alternate) sequence. Before the first test, participants were told that the Xs had followed a repeating sequence in the training phase and that they would now be presented with short sequences of six trials, some of which were part of the training sequence and some of which were not. They were asked to respond to each trial as before and then to judge whether the sequence was old or new and rate how confident they were in their judgment. As in the previous experiments, confidence ratings were made by first clicking on option buttons labeled “old” and “new” and then clicking on buttons labeled “very sure”, “relatively sure”, and “guess”. Because the main goal of experiment 4A was to replicate the study of Shanks et al. (2003, Experiment 3), the confidence ratings were likewise converted to a scale ranging from 1 to 6 (1 very sure new, 2 relatively sure new, 3 guess new, 4 guess old, 5 relatively sure old, 6 very sure old). There were 24 test sequences in total, presented in a randomized order for each participant. Twelve of the sequences were constructed by starting at each serial location of SOC1, and 12 were constructed by starting at each serial location of SOC2. Thus, the SOC1 test sequences were old for participants trained on SOC1 and new for those trained on SOC2 (converse for the SOC2 sequences). Two dependent variables were used in the tests: RTs to targets and recognition judgments.

4.4.2 Results

4.4.2.1 Learning Phase

Reaction times for participants trained with SOC1 and SOC2 were combined in the following analyses. The RTs to the first two targets of each block were excluded, because their locations could not be predicted. Figure 14 shows the mean RTs obtained over the training phase and the average percentage of errors. An ANOVA with block as a within subject variable revealed a significant effect of block, $F(11, 600) = 48{,}860$, MSe = 55.095, $p < .01$. Error rates ranged between 3% and 4% and did not change significantly over blocks $\underline{F} < 1$.

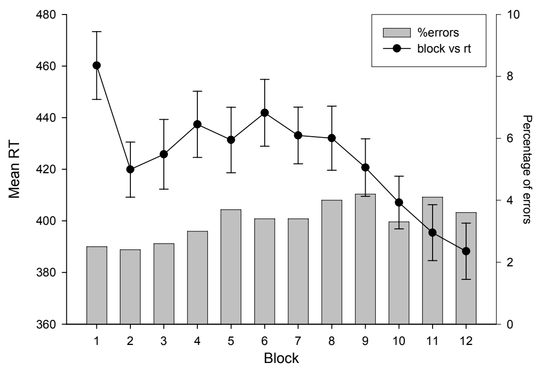

Figure 14: Learning Phase. Mean reaction times (RTs) in milliseconds (left axis) across blocks and standard errors of the mean. Mean Percentage of errors (right axis) across blocks.

4.4.2.2 Tests

<u>Priming:</u> Figure 15 shows the mean RTs for old and new test sequences before and after the retention interval of one week. A 2 (time of testing: pre vs. post) X 2 (type of string: new vs. old) repeated measures ANOVA revealed a significant main effect of time of testing, $F(1, 49) = 43{,}558$, MSe = 2960,44, $p < .01$, and a significant main effect of type of string, $F(1, 49) = 73{,}44$, MSe = 619,6 $p < .01$, but no significant interaction between time of testing and type of string, $F(1, 49) = 2{,}37$, $p = {,}13$. These results indicate that the RT advantage for old over new items did not change with time. Thus, the implicit knowledge measure was not affected by the retention interval. This particular finding replicates the findings of the 3 previous experiments with artificial grammars.

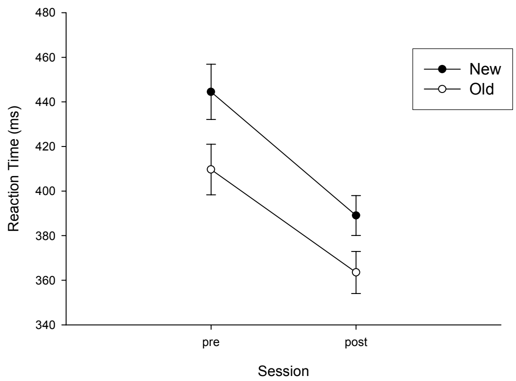

Figure 15: Mean reaction times to old and new test sequences in Experiment 4A. Measurements were conducted immediately upon completion of the learning phase (pre) and after a delay of 7 days (post). Error bars depict standard errors of the mean.

Recognition: For recognition, an analysis closely modeled after Shanks et al. (2003) was performed. Mean recognition ratings for old and new sequences are shown in Figure 16 (higher ratings correspond to greater confidence that the sequence is old). It is clear that participants were able to differentiate between old and new sequences, but their recognition ability decreased with time. A 2 (time of testing: pre vs. post) X 2 (type of string: new vs. old) repeated measures ANOVA confirmed this observation. There was a significant main effect of time of testing, $F(1, 49) = 17{,}340$, MSe =,312, $p < .01$, a significant main effect of type of string, $F(1, 49) = 27{,}58$, MSe = ,359 $p < .01$, and more importantly a significant interaction between time of testing and type of string, $F(1, 49) = 10{,}835$, MSe = ,249 $p = {,}002$.

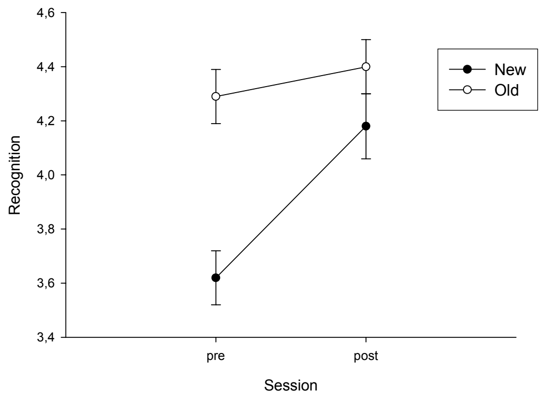

Figure 16: Mean recognition ratings for old and new test sequences in Experiment 4A. Participants responded to 12 old and 12 new sequences and made recognition judgments for each sequence (1= certain new, 6= certain old). Measurements were conducted immediately upon completion of the learning phase (pre) and after a delay of 7 days (post). Error bars depict standard errors of the mean.

Additionally, I tested whether recognition judgments held with higher confidence displayed a different pattern of forgetting that recognition judgments held with lower confidence. Therefore d' scores were separately computed for cases (a – "very sure" and "relatively sure") and (b –"guess"). The d's for case (a) were .49 at the pre and 0.12 at the post time of assessment. The d's were significantly different from zero at the pre $F(1, 49) = 19.35$, MSe = 1.79, $p < .01$ and at the post times of testing $F(1, 49) = 43.42$, MSe = .28, $p < .01$. In addition, the d's differed for the two times of testing, $F(1, 49) = 8.61$, MSe = .40, $p = .005$. Thus, the confidence ratings held with higher confidence show a clear pattern of forgetting of rapid decay imitating the overall findings.

However the analysis of d's for case (b) were not conclusive because only 21 of 50 participants used the "guess" category response, which leaves many empty cells in the d' computations. The mean d's were .75 at the pre and .33 at the post time of assessment. The d's marginally differed from zero at the pre time of testing $F(1, 20) = 19.35$, MSe = 1.79, $p < .057$ but not at the post time of testing $F < 1$. The d's did not differ for the two times of testing, F(1, 20) = .997, MSe = 1.88, $p = .33$.

4.4.3 Discussion

Implicit knowledge in the form of priming (RT savings) was preserved after a retention interval of 7 days but explicit knowledge in the form of recognition scores decreased. This single finding constitutes the first demonstration of different forgetting rates for implicit and explicit knowledge in a SRT task.

However, some important arguments may be raised against this conclusion. First, one could argue that the dissociation is produced by a source confusion error due to the fact that lures become more familiar during tests. According to this alternative account, the source confusion would have increased the false alarm rate which, in turn, would have introduced noise to the explicit measure estimated by the recognition scores. To address this issue, it is important to recall the results of Experiments 1, 2, and 3. Overall, these experiments showed that repetition of the same testing items is not a cause for the dissociation of forgetting patterns of implicit and explicit knowledge. These studies point to the possibility that interference, conceived not as a response competition phenomenon (e.g., cue-overload or source confusion) but as an obstruction in the process of consolidation, might be responsible for the observed dissociation.

Second, one might argue that RT priming is not sensitive enough to variations of the underlying knowledge strength. To address this issue, one may test empirically the ability of priming as a measure of implicit knowledge to drop to a base-line level when a larger retention interval is introduced. The rationale for such a test would be to show that if RT is not susceptible to decrements of knowledge strength but only, for example, to a sampling or other statistical error, then one would expect priming to be preserved after an extra long retention interval. However, if priming is susceptible to changes in knowledge strength, then this measure should drop to a floor level after a long delay. This latter empirical test was undertaken in Experiment 4B.

4.5 Experiment 4B: Forgetting after 100 days

The previous Experiments 1, 2, 3 and 4A have shown a striking dissociation in the forgetting of explicit and implicit knowledge. Explicit knowledge decreased after a 1-week interval, but implicit knowledge was preserved. An important question derived from this functional dissociation is whether implicit and explicit knowledge of the same information is forgotten at different rates, and more precisely, which function best describes this apparent difference in the forgetting patterns. In this regard, Tunney (2003) conjectured that (1) the decay in both explicit and implicit knowledge might be consistent with a power law (Ebbinghaus, 1885; Wixted, 1990;

Wixted and Ebbesen, 1991) but that (2) the constants to fit each curve would be different.

The first assumption of Tunney (2003) was reasonably supported on the observation, with 3 data points (day 0, day 7, and day 14), that explicit knowledge displayed an evident non linear pattern of initial rapid forgetting (at day 7) toward asymptote, whereas implicit knowledge remained stable across all of 3 retention intervals. However, the assumption that forgetting of implicit knowledge might be consistent with a power law was not empirically warranted because RT priming did not show any decay in the absolute. In fact, neither Tunney's (2003) experiment nor previous data in this dissertation showed any loss of implicit knowledge. In the first case (Tunney, 2003), implicit knowledge remained constant even after 2 retention intervals (7 and 14 days; see Tunney, 2003, Table 1). In the previous experiments of this dissertation, a complete retention of implicit knowledge has been similarly shown after 1 retention interval of 7 days. However, there is evidence that implicit knowledge, at least in SRT tasks, is not entirely immune to forgetting after a longer retention interval of 1 year (Willingham and Dumas, 1997). Therefore, one may ask whether a retention interval that lies between these two extreme values of 14 days and 1 year may be suitable to obtain a graded reduction of implicit knowledge.

The goal of Experiment 4B was to test whether implicit knowledge decreases when the retention interval is extended up to 100 days. Of course, explicit measures were also taken in order to compare the forgetting curves of implicit and explicit knowledge. The rationale is that conducting at least 3 assessments of knowledge retention (day 0, day 7, and day 100), provides an opportunity to evaluate whether the rate of forgetting of implicit knowledge might be consistent with a power law. If it is found that implicit knowledge is retained after 100 days, then the assumption of an initial rapid forgetting toward asymptote would be disconfirmed. On the other hand, if implicit knowledge declines, then it is possible to fit the forgetting of implicit and explicit knowledge to power functions.

For Experiment 4B, the participants of Experiment 4A were called up again to participate in the study after a delay of 100 days (in average). From the 50 participants who completed Experiment 4A, 41 participants were able to participate in Experiment 4B.

4.5.1 Method

The procedure, materials, and methods were exactly the same as were used for the second test of Experiment 4A. The mean retention interval across participants was 101.46 days, *SD* 3.37 (range from 96 to 109 days).

4.5.2 Results

After 100 days (in average) both implicit and explicit knowledge decreased. The mean d' (-0.15) was not significantly different from zero $F(1, 40) = 1.62$, MSe = .547. $p = .211$. Similarly, the mean RT priming (-1.87) was not significantly different from zero $F < 1$.

Additionally, I wanted to extend and compare the findings of Experiment 4A with the findings of Experiment 4B. Thus, I compared implicit and explicit knowledge on the 3 times of assessment for the 41 participants who completed Experiments 4A and 4B. As assessed in the original study of Shanks et al. (2003) explicit knowledge was estimated with confidence ratings that participants provided after every recognition (hereafter recognition ratings) while implicit knowledge was estimated with RT priming.

4.5.2.1 Priming

A 3 (time of testing: day 0, day 7 and day 100) X 2 (type of string: new vs. old) repeated measures ANOVA on RTs revealed a significant main effect of time of testing, $F(2, 80) = 20{,}306$, MSe = 3087,663, $p < .01$, a significant main effect of type of string, $F(2, 80) = 60{,}001$, MSe = 458,443 $p < .01$, and a significant interaction between time of testing and type of string, $F(2, 80) = 16{,}854$, MSe = 507,495 $p < .01$. Figure 17 illustrates these data.

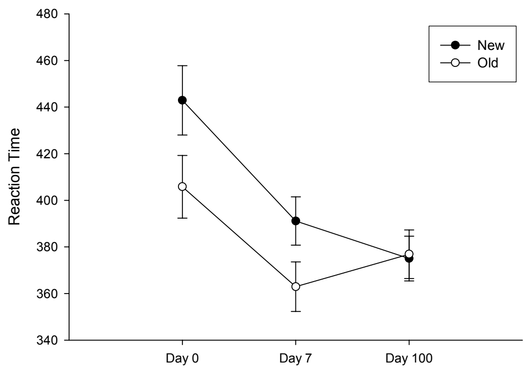

Figure 17: Mean reaction times to old and new test sequences in Experiment 4B. Measurements were conducted immediately upon completion of the learning phase (Day 0), after a delay of 7 days (Day 7), and a delay of 100 days (Day 100 / on average). Error bars depict standard errors of the mean computed only for 41 participants that took part in all three sessions.

4.5.2.2 Recognition

A 3 (time of testing: day 0, day 7 and day 100) X 2 (type of string: new vs. old) repeated measures ANOVA for recognition ratings revealed a significant main effect of time of testing, $F(2, 80) = 7{,}837$, MSe =,318, $p = .01$, a significant main effect of type of string, $F(2, 80) = 10{,}435$, MSe =,332 $p = .02$, and a significant interaction between time of testing and type of string, $F(2, 80) = 12{,}553$, MSe =,289 $p < .01$

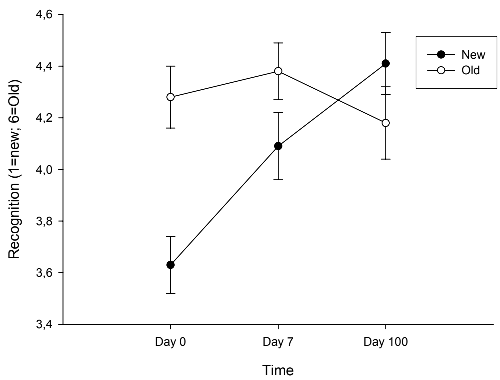

Figure 18: Mean recognition ratings for old and new test sequences in Experiment 4B. Participants responded to 12 old and 12 new sequences and made a recognition rating for each sequence (1= certain new, 6= certain old). Measurements were conducted immediately upon completion of the learning phase (Day 0), after a delay of 7 days (Day 7), and after a delay of 100 days (Day 100). Error bars depict standard errors of the mean.

In order the make more evident the comparison between the forgetting rates of implicit and explicit knowledge, I converted, first, both the RTs to new and old items and the recognition ratings to an equivalent scale. RTs were converted to dRT (see Formula 1 on page 82). Recognition ratings were converted to a dREC scale. I derived dREC from Equation 1 by replacing the data for RTs with the mean recognition ratings and their corresponding standard deviations.

$$dREC = \frac{M_{old} - M_{new}}{(SD_{old}/2 + SD_{new}/2)}, \qquad (2)$$

Figure 19 shows the results of these conversions. The implicit measure dRT and the explicit measure dREC are on the same scale of measurement.

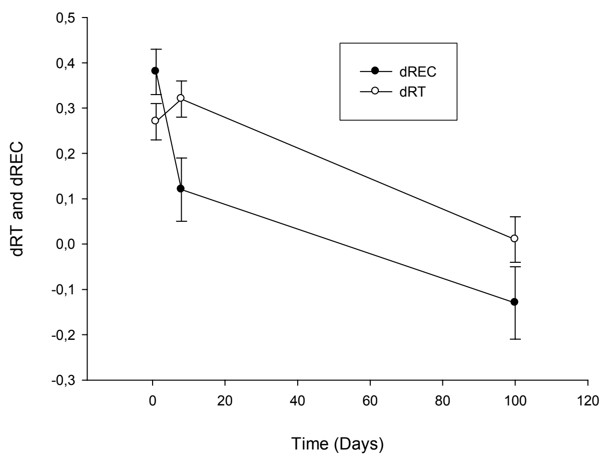

Figure 19: Results for implicit knowledge (dRT) and explicit knowledge (dREC) in the same standardized scales computed according to Equation 1 (p. 82) and Equation 2 (p. 102) respectively. Tests were conducted (1) immediately after the learning phase, (2) after a retention interval of 7 days, and (3) after a retention interval of 100 days. Error bars depict standard errors of the mean.

Second, I fitted the forgetting rates of dREC and dRT to power functions. Previous attempts to compare the best fitting parameters of forgetting data to different curvilinear functions (e.g., exponential, hyperbolic, logarithmic, etc.), have shown that the power function may account for nearly all of the variance (98.7%) of memory performance on long-term (up to 15 days) recognition performance (see Wixted & Ebbesen, 1991, Experiment 2). When the general form of the power function ($y=at^{-b}$) is applied to memory decay it is assumed that *a* corresponds to maximal memory strength, *t* corresponds to time, and *b* corresponds to the forgetting rate. The power function for the group data of Experiment 4 showed a better fit (r^2 = 0.8) to performance on the explicit test (forgetting rate b = -0.77), than the fit (r^2 = 0.5) to performance on the implicit test (forgetting rate b= -0.22).

4.5.3 Discussion

Experiment 4B demonstrates that RT priming, a purported measure of implicit knowledge, decreases when enough time has passed between tests. This particular finding is in line with previous evidence (Willingham & Dumas, 1997) showing that implicit knowledge involved in motor performance is not indefinitely resistant. Additionally, the experiment shows that an interval of approximately 100 days is sufficient to demonstrate a decline of implicit knowledge in SRT tasks. This constitutes the first evidence that implicit and explicit knowledge, compared on the same metric, may have different forgetting patterns in the SRT task.

Regarding the question of whether the forgetting rates of implicit and explicit knowledge may be described by power functions with different exponential parameters, the power function showed a better fitting for the decay of explicit knowledge than for the decay of implicit knowledge, which indicates that implicit knowledge apparently does not follow the typical pattern of initial rapid forgetting toward asymptote. However, because only 3 retention intervals were used, more empirical evidence is required to estimate the exact form of forgetting for implicit knowledge.

4.6 Simulations

The broader goal of the simulation was to identify which parameters needed to be modified in the single-system model proposed by Shanks et al. (2003), to simulate the different patterns of forgetting for implicit and explicit knowledge. In Chapter 2, I presented the main theoretical characteristics of single and dual models of learning. Especially relevant for the goal of this dissertation is the ability of the so- called *permissive* unitary model of implicit learning (Shanks, et al., 2003) to account for the data. One of the assets of this model is the ability to simulate dissociations between priming and recognition, purported measures of implicit and explicit knowledge respectively, without the need to appeal to separate memory systems for the two forms of knowledge. One of the key assumptions of the model is that both implicit and explicit measures are correlated with the same underlying knowledge strength variable called familiarity. Because familiarity determines both priming and recognition, dissociations are accounted for by appealing to different sources of error for each measure. Accordingly, the model assumes greater error terms for recognition than for priming. Thus, when performance on recognition is equal or close to zero, priming can still be reliably shown. However, the model does not make any theoretical assumption about the nature of the errors. One possibility is to assume that independent sources of error occur in the processes that translate the underlying memory strength into priming and recognition performance. Another possibility is that errors are due to undetermined measurement noise specific for every task.

Using this strategy, the model has been successfully applied to account for dissociations on SRT and memory tasks. The goal of this section is to test the ability of the model to account for the dissociation in forgetting for implicit and explicit knowledge presented in the empirical section. I confer special attention to the data of Experiments 4A and 4B. The results are especially suitable to test the model because they are based on the same task that underlies the model described by Shanks et al., thus the application of the model requires minimal assumptions. The set of simulations may be also assumed to involve qualitative descriptions of the results of Experiments 1, 2 and 3. The reason for this latter claim is that, as explained in the introduction, the artificial grammar paradigm was realized in a way similar to a SRT task in the sense that participants had to respond by key presses on sequential regularities. In the first case, the regularity was determined by an artificial grammar; in the second case, the regularity was determined by a 12-elememt sequence.

The model computes RTs as follows:

$$RT = b + 100\,(1-f) + 500\, e_{rt} \qquad (3)$$

where familiarity (f) is a normally distributed random variable, e_{rt} is a uniformly distributed random error and b is the slope of RT.

Recognition ratings are computed as:

$$J = 2\,f + e_j + 1 \qquad (4)$$

where the same sampled value of familiarity f is used to compute recognition, e_j is an independent normally distributed random error with mean and standard deviation higher than e_{rt}. Table 1 summarizes all parameters of the model.

Table 1: *Original parameters of the model of Shanks et. al (2003).*

Parameter	Meaning	Value
b	RT Intercept	80 (RSI)
f_{new}	Familiarity of new items	.40
f_{old}	Familiarity of old items	.60
σf	Standard deviation of f	.40
e_{rt}	Error in RT's	.50
σe_{rt}	Standard deviation of e_{rt}	.20
e_{j}	Error in recognition	1.5
σe_{j}	Standard deviation of e_{j}	1.5

Note that the mean familiarity for old items is slightly higher than the mean familiarity for new items, this difference in familiarity (f_{old} - f_{new} = .2) is enough to show significant values of priming without a concomitant sizable degree of recognition. This property of the model has made it suitable to simulate findings in which recognition is at chance when priming is above chance (Shanks et al., 2003).

In order to simulate the data of Experiments 4A and 4B as close as possible to the original model I followed two steps. First, I computed the best-fitting parameters of the model for the empirical data, second, I entered these parameters as input to a simulation.

4.6.1 Finding the best-fitting parameters

In the original application of the model (Shanks et. al, 2003), no attempt to obtain best-fitting parameter values was done and no conventional measures of fit such as sum of squared error (SSE) were presented. The reason is that the model was fitted simultaneously to two types of data that involved different measurement scales (RT and recognition), and it was argued that there is no objective method of weighting the relative goodness of fits to the two measures to yield a single measure of fit. In order to overcome this difficulty, I converted the implicit and the explicit measures of the empirical data of Experiments 4A and 4B to the same scales (dRT and dREC) by using the model suggested by Poldrack and Logan (1997).

For the implicit measure I used the mean RT and their corresponding standard deviation as indicated in Formula 5.

$$dRT(obs) = \frac{RT_{new} - RT_{old}}{(SD_{old}/2 + SD_{new}/2)}, \quad (5)$$

where dRT(obs) is the degree of discriminability observed in Experiments 4A and 4B for RTs. *RTnew* and *RTold* are the mean observed RTs for new and old items, and SDs are the corresponding standard deviations of RTs.

For the explicit measure I used the mean recognition ratings and their corresponding standard deviations as indicated in Formula 6.

$$dREC(obs) = \frac{REC_{old} - REC_{new}}{(SD_{old}/2 + SD_{new}/2)}, \quad (6)$$

where dREC(obs) is the degree of discriminability observed in experiments 4A and 4B for recognition ratings, *RECnew* and *RECold* are the mean recognition scores for new and old items, and SDs are the standard deviations of the recognition scores.

Second, I also converted the *predicted* values of the original model (RT and J) from Formulas 3 and 4 (p. 104), to the same comparable scales dRT(predicted) and dREC(predicted). Because the standard deviations of the error terms for RT (σe_{rt}), recognition (σe_j), and familiarity (σf) are known (provided in Table 1), it is possible to replace Formulas 1 (p. 82) and 2 (p. 102) by Formulas 3 and 4 respectively. This enabled me to compute the predicted *dRT* and *dREC* values of the model by applying the propagation of uncertainty (see e.g., Taylor, 1982, Chapter 3) for statistical independent measures as follows (for more detail see Appendix 3):[2]

$$dRT(predicted) = \frac{f_{old} - f_{new}}{\sigma f + 5\,\sigma e_{rt}}, \quad (7)$$

$$dREC(predicted) = \frac{2(f_{old} - f_{new})}{2\sigma f + \sigma e_{j}}, \quad (8)$$

[2] The description of the variables of formulas 7 and 8 are exactly the same as those presented in Table 1. Therefore, dRT and dREC predicted by the original model, without any modifications, correspond to .14 and .17 respectively.

Third, I computed the best-fitting parameters that minimized the total sum of square errors (SSE) of the differences between the *observed* and the *predicted* values at the 3 times of testing for Experiments 4A and 4B (see Dodson, et al., 1998). To obtain the best-fitting parameters I used the Solver-tool of Excel, which uses the method of gradient descent (see Dodson, et al., 1998). My general strategy was to select a submodel with the fewest number of parameter modifications that adequately fit the data. As can be seen in Formulas 7 and 8, there are basically 3 sorts of parameters that can be fitted, (a) three familiarity related parameters (f_{old}, f_{new}, and σf), (b) one RT related parameter σe_{rt}, and (c) one recognition related parameter σe_j. I set as an a priori criterion to fit the mean familiarity (f), not the standard deviation of familiarity. Table 2 shows the results of these fits. I provide the 3 basic parameters against the SSE (and the original model parameter set is also included to facilitate comparisons). These results were obtained by changing one parameter at a time. For example, when all parameters of the original model are kept constant, the SSE is close to .1. When one parameter is fitted (i.e., standard deviation of error in recognition: σe_j), and all other parameters are kept constant, then the fit of the submodel is close to .05, etc. As can be seen, changes in familiarity convey the best fit, followed by changes in the standard deviation of recognition. This happens because familiarity has to change in order to encompass the particular initial knowledge strength at T1 after learning in Experiment 4A, in which deterministic sequences were used instead of probabilistic sequences. Recall that the use of deterministic sequences was necessary to avoid floor effects, but produced also higher degrees of priming and recognition than predicted by the model, which was originally designed to describe performance on probabilistic sequences. For example, familiarity at the first time of testing on the original model is .2 whereas the required value of familiarity to fit the first time of testing in the current data is .42.

Table 2: *Results of the best-fitting parameter estimation procedure. For every parameter the SSE is shown when all other parameters are kept constant.*

Parameter	Meaning	Value
Shanks et. al	Original parameter set	0,10
σe_{rt}	Standard deviation of e_{rt}	0,05
σe_{j}	Standard deviation of e_{j}	0,04
f	Overall familiarity	0,03

With these preliminary results at hand, I decided to select the standard deviation of error in recognition (σe_j) and familiarity (f) as the parameters to be used for the simulation of the empirical results of Experiment 4, because these two parameters showed the least SSE (see Table 2).

A final a priori restriction that I imposed on the parameter estimation procedure was that familiarity should not increase with time, because it is counterintuitive that memory improves without training with the simple passage of time.

Table 3 shows the results of the procedure explained above and the corresponding best-fitting parameter values for each time of testing. These values were used for the Simulation described next. When these parameters are used, the SSE equals .0012. Interestingly, the overall familiarity value (f_{old} - f_{new} = .42) does not change between the first and the second times of testing but there is a notable increment in the standard deviation of the error in recognition (σe_j).

Table 3: *Best-fitting parameters that minimize the SSE between the predicted and the observed data for dREC (explicit measure) and dRT (implicit measure) at 3 different times of testing.*

Parameter	Meaning	Time	Value
f_{new}	Mean familiarity of new items	1	.29
f_{old}	Mean familiarity of old items	1	.71
$\sigma(e_j)$	Standard deviation of e_j	1	1.26
f_{new}	Mean familiarity of new items	2	.29
f_{old}	Mean familiarity of old items	2	.71
$\sigma(e_j)$	Standard deviation of e_j	2	6.08
f_{new}	Mean familiarity of new items	3	.52
f_{old}	Mean familiarity of old items	3	.48
$\sigma(e_j)$	Standard deviation of e_j	3	.01

4.6.2 Simulating the empirical results of Experiment 4A and 4B

To implement the Simulation I used the Simulink®-toolbox of Matlab®, which enabled me to control the input parameters (mean and standard deviations for each normally distributed random parameter) and the number of runs. Figure 20 shows, for example, how the model was implemented to simulate the performance at the first time of assessment. Note that the same familiarity values are involved in the generation of RTs and recognition while different sources of error (e_{rt} and e_j) produce the dissociations.

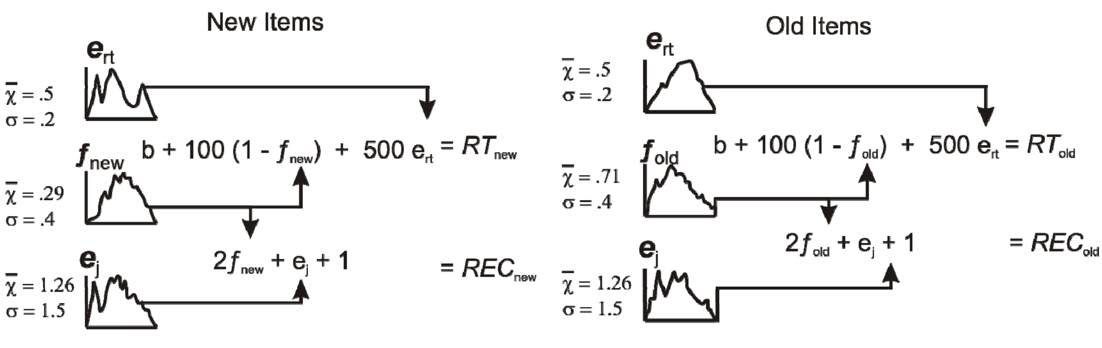

Figure 20: Example of the implementation in Simulink of the Formulas 3 and 4 to simulate performance on implicit (RT) and explicit (REC) tests for new and old items at T1.

Closely modeled to the data of Experiments 4A and 4B, I simulated 50 participants at 3 assessment times. For each simulated participant, I generated 12 RTs and 12 recognition ratings for new and old items with the parameters shown in Table 3. All other parameters and constants were exactly the same as those of the original model of Shanks et. al. (2003), see Formulas 3, 4, and Table 1. The old and new values were then averaged to yield a single reaction time and recognition rating for new and old items at 3 times of testing for every simulated participant. Then, the predicted average implicit (dRT) and explicit (dREC) performances were computed according to the above Equations 7 and 8, respectively. Note, first, that simulations at the first time of testing (T1) convey a modification in familiarity relative to the original parameter values of the model. Second, the standard deviation of the error in recognition (σe_j) increased at the second time of assessment (T2), relative to the first time of assessment (T1), but familiarity values remained constant. Third, simulation of the third time of testing (T3) comprises a reduction in both overall familiarity ($f_{old} - f_{new} = -0.04$) and in the standard deviation of the error in recognition, relative to T2.

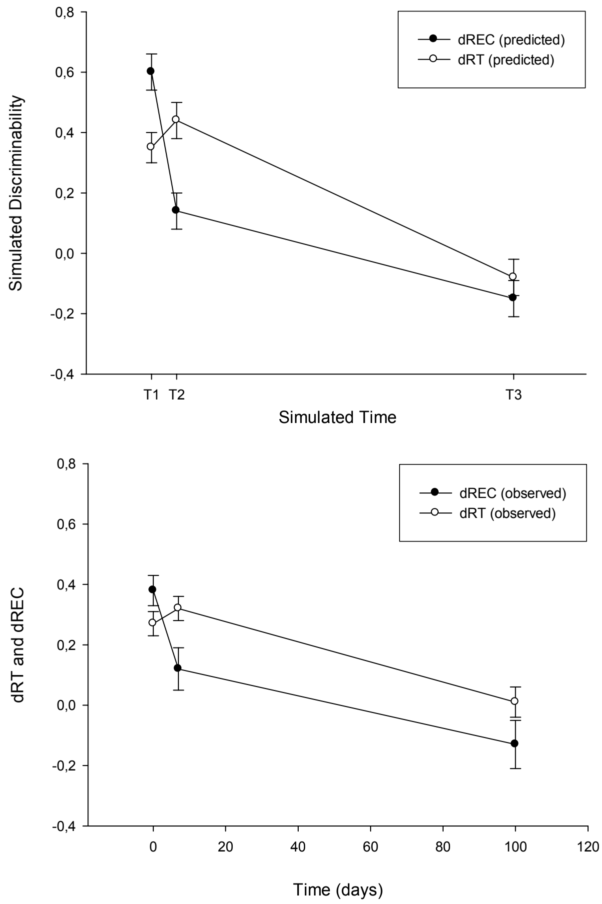

Figure 21: Upper panel, results of the simulation of implicit (dRT) and explicit (dREC) performance with the parameters presented in Table 3. Bottom panel, results of Experiments 4A and 4B.

Figure 21 shows the simulated results for dRT and dREC plotted in the same way as the observed results of Experiments 4A and 4B. This pattern of results is strikingly similar to the results of Experiments 4A and 4B.

The results of the Simulation are also statistically very similar to the results of the empirical data. Specifically, regarding the comparison with Experiment 4A, I ran two ANOVAs comparing the first (T1) and the second (T2) times of assessment independently for the simulated RTs and recognition ratings. On the one hand, a 2 ("time of testing": T1 vs. T2) X 2 (type of string: new vs. old) repeated measures ANOVA was computed using the simulated *RTs*. This analysis revealed no significant main effect of time of testing, $F(1, 49) = ,246$, MSe = 744,540 $p = ,939$, a significant main effect of type of string, $F(1, 49) = 154,422$, MSe = 993,863 $p < .01$, and no significant interaction between time of testing and type of string, $F(1, 49) =$

1,325, MSe = 1052,486, *p* = ,255. On the other hand, a 2 ("time of testing": T1 vs. T2) X 2 (type of string: new vs. old) repeated measures ANOVA was computed using the *recognition ratings.* This analysis revealed a significant main effect of time of testing, $F(1, 49) = 4{,}568$, MSe = ,2,15, $p = ,038$, a significant main effect of type of string, $F(1, 49) = 41{,}816$, MSe = ,357 $p < .01$, and a significant interaction between time of testing and type of string, $F(1, 49) = 13{,}535$, MSe = ,225 p = ,001.

In the case of Experiment 4B, I ran two ANOVAs comparing the 3 times of assessment independently for the simulated RTs and recognition ratings. A 3 ("time of testing": T1, T2, and T3) X 2 (type of string: new vs. old) repeated measures ANOVA on *RTs* revealed no significant main effect of time of testing, $F(2, 98) =$ 1,357, MSe = 949,250, $p = ,262$, a significant main effect of type of string, $F(2, 98) =$ 69,161, MSe = 710,287 $p < ,01$, and a significant interaction between time of testing and type of string, $F(2, 98) = 23{,}890$, MSe = 884,869 $p < .01$. A 3 (time of testing: T1, T2, and T3) X 2 (type of string: new vs. old) repeated measures ANOVA for *recognition ratings* revealed a significant main effect of time of testing, $F(2, 98) =$ 3,244, MSe =,184, $p = ,04$, a significant main effect of type of string, $F(2, 98) =$ 27,374, MSe =,291 $p < ,01$, and a significant interaction between time of testing and type of string, $F(2, 98) = 29{,}132$, MSe =,177 $p < .01$

4.6.3 Discussion

The goal of the Simulation was to find out how the single-system assumptions involved in the computational model of Shanks et al. (2003) may account for the pattern of empirical dissociations reported in Experiment 4. A crucial assumption of the model is that dissociations between implicit and explicit tests are not the product of different knowledge-bases (i.e., implicit and explicit knowledge) but that dissociations are mainly due to the involvement of different sources of error for the implicit and the explicit tests. In other words, implicit and explicit tests measure the strength of the same memory trace (called *familiarity* in the model) and dissociations are simply the behavioral expression of using different tasks. Therefore, an important question derived from this assumption is whether different error terms are also suitable to simulate boundary conditions in which the strength of the memory trace changes as a consequence of forgetting. In order to quantitatively test this prediction of the model, I first computed the exact values of the parameters related to the error terms and related to familiarity that best fitted the empirical results. In a second step, I simulated the performance on implicit and explicit tests at 3 different times of assessment with the best fitting parameters previously obtained.

The simulated results showed an striking statistical similarity to the empirical data when the parameters related to familiarity and error in recognition are allowed to fluctuate in a very atypical pattern. More specifically, the model predicted that (1) familiarity should be unaffected after a retention interval of 7 days and, at the same time, (2) the error term for recognition performance should dramatically increase. Plainly, the increase in error is crucial to simulate the boundary condition.

How to justify the assumption of an increase in error in the explicit measure after a retention interval? Clearly, it is essential to ask what is the meaning of the error term, and how it is integrated into a single-system account. In this regard, in the theoretical section, I identified two slightly different kinds of permissive single-system models. One kind of model emphasizes that error involves the action of internal cognitive mechanisms responsible for the conversion of knowledge strength into overt performance (e.g., Humphreys, 1989); a sort of regular or constant error (e.g., Suppes, et al., 1989). The other type of model emphasizes that error terms stem from the external properties of the task such as difficulty or sensitivity (e.g., Zaki, et al., 2003); a sort of irregular or random error (e.g., Taylor, 1982). I suggest that error has to be interpreted in the first way. Because the model does not predict a decrease in knowledge strength after a delay of 7 days but it does predict an increase in the error term of recognition performance (see Table 3), the most plausible assumption seems to be that the recognition task constitutes a more indirect test of knowledge strength than the implicit RT priming task (Tunney, 2003). To hold this assumption, within the logic of the model, error may only be interpreted as the operation of additional mechanisms that access (or convert) the knowledge base to overt recognition performance. The alternative assumption that error simply reflects the statistical level of sensitivity (or difficulty) of the tasks may be untenable (at least for the specific boundary condition involved in the study of forgetting rates). This is so, because one would need to further assume that the threshold for explicit knowledge changes with time; which, by definition, contradicts the very concept of what a threshold is. Therefore, the best way to interpret the increase in error terms for recognition, (without abandoning a single-system perspective), seems to attribute error to a specific mechanism responsible for the expression of explicit performance.

To summarize, the key question is whether an increase in the error term for recognition without a concomitant reduction in familiarity constitutes a reasonable assumption for modeling the data of Experiment 4. The model (Shanks et al. 2003) predicts that (1) the error parameter for recognition after 1 week is about 5 times bigger than the error term for recognition before the retention interval while (2) the familiarity parameter remains constant. In other words, the model implies that the strength of the memory trace (familiarity) involved in the recognition and in the priming tasks is not weakened after the retention interval . Apparently, the model implies that the memory traces *cannot* be adequately expressed in recognition performance but, at the same time, they *can* be adequately expressed in priming performance. From the perspective of the model, this dissociation can only be attributed to different translation processes of the same knowledge base to different sorts of overt performance involved in recognition and priming. The alternative assumption that an increase in the error term for recognition simply reflects a change in the external properties of the recognition task (i.e. difficulty) seems unreasonable because all objective characteristics of the tasks were constant across the retention intervals. Additionally, the assumption that familiarity remains constant after 1 week appears to contradict a body of research on recognition memory showing an initial rapid forgetting toward asymptote (e.g., Wixted, 1990) usually attributed to a decrease in the strength of memory traces. Of course, the model may still be consistent with some theories that attribute forgetting to interference in the process of knowledge expression or retrieval failures (e.g., Shiffrin, 1970).

5 Conclusions

The basic empirical question addressed in this dissertation is whether implicit and explicit knowledge are forgotten at different rates. In the first chapter, implicit knowledge was defined as knowledge that is unintentionally acquired and unintentionally retrieved. This definition has proven to be useful insofar as it conforms to most common operational criteria used in research on implicit learning and implicit memory. In Chapter 1, I also argued that the study of the temporal dynamics of implicit and explicit knowledge involves a graded perspective that is useful to overcome the traditional criteria used to take single dissociations as indices of an implicit system. First, it does not require the assumption of selective influence. Second, it recognizes the potential role of different sensitivities of implicit and explicit measures. Third, it involves the assumption that knowledge strength may gradually increase with training and decrease over a retention interval. Therefore, I suggested that studying the specific mechanisms that generate dissociations may constitute a potentially productive approach to decide between single and multiple memory systems. Then, I discussed the foundations and key paradigmatic examples of single and multiple systems models of memory and learning. This discussion showed that the so called permissive single-system models are gaining importance because they can parsimoniously account for a wide range of dissociations.

In the second chapter, I presented an appraisal of the current empirical evidence according to a set of a priori criteria recommended to evaluate the pivotal distinction between implicit and explicit memory systems. Briefly, the empirical evidence for three of these criteria: (a) functions, (b) processes, and (c) phylogenic development, appears to support the multiple-system view. But three other criteria (a) representation format, (b) ontogenetic development, and (c) neural substrates, are still the source of considerable debate. The analysis showed that one key open question concerns whether implicit and explicit forms of knowledge are forgotten at different rates. Roughly speaking, finding similar patterns of forgetting for implicit and implicit knowledge would further support the assumption of a single-system, while finding different patterns would add to the body of evidence supporting the assumption of multiple memory systems.

Consequently, the empirical section was devoted to compare the forgetting rates for implicit and explicit knowledge in artificial grammar and serial reaction time tasks. The results went beyond those previously reported in several ways: in Experiments 1 and 2, I used a design in which measures of implicit and explicit knowledge of artificial grammars were compared after a delay of 7 days. These results showed clearly that implicit and explicit knowledge decline at different rates. These experiments also provided important empirical evidence to distinguish between dissociations in forgetting rates due to (1) decay, understood as a progressive degradation of memory strength (Experiment 2), and due to (2) source confusion induced by the repetition of lures at different times of assessment (Experiment 1). The empirical results were consistent with the assumption that knowledge strength, (not only bias or errors) produced the decrease during the retention interval.

In Experiment 3, an interference task was introduced to investigate the mechanism that may degrade knowledge strength. Explicit knowledge appeared to be more susceptible to interference than implicit knowledge. The experiment empirically distinguished between two possible mechanisms that may potentially account for different patterns of forgetting for implicit and explicit knowledge. One mechanism concerns forgetting that hinders the consolidation processes of explicit knowledge. The other mechanism concerns forgetting of implicit and explicit forms of knowledge due to decay. Taken together, Experiments 1, 2, and 3 entail significant constraints to single-system models. In particular, the most restrictive versions of the single-system theory (e.g., Perruchet & Vinter, 2002) assume that explicit knowledge emerges mechanically as a by-product of knowledge strength. The empirical findings are inconsistent with this view because such models predict that both forms of knowledge decay at similar rates when the common underlying familiarity (knowledge strength) decreases with the passage of time or interference.

Experiments 4A and 4B also showed different forgetting patterns of implicit and explicit knowledge in a Serial Reaction Time task. Experiment 4A constitutes the first empirical evidence showing dissociations in the forgetting patterns of implicit and explicit knowledge on this specific task. Experiment 4B showed that both measures decay to a baseline level when a third retention interval of 100 days is introduced, which is specially relevant to make the argument that RTs are also sensitive, in the absolute, to variations in knowledge strength. The latter experiment also showed that a power function of forgetting more adequately described the forgetting pattern of explicit knowledge than the forgetting pattern of implicit knowledge.

The simulations showed that a computational single-system model can only accommodate the previous empirical results when it is assumed that the error term for recognition (the explicit measure) increases with time. These findings entail significant constraints for permissive single-system models (e.g., Shanks et. al. 2003). Single-system models need to specifically address the question about the psychological meaning of error terms. One possibility is to take error terms as simple statistical variance due to different sensitivities or thresholds for implicit and explicit tasks (see Figure 2 for an example of this idea). The other possibility is to take error terms as occurring in the translation process from the memory representation to overt behavior. The results of the simulations favored the second alternative, because it is not plausible to assume that a threshold in the sensitivity of a task changes with time. For example, Figure 2 (p. 25) illustrated the first possibility, that is, a simple permissive single-system model with different thresholds for implicit and explicit tests. However, the results of the simulations showed that the model assuming different thresholds does not correspond to the predictions of the computational model of Shanks et al. (2003) because this latter model predicted that familiarity did not change from the first (T1) to the second (T2) times of assessment, rather, the model predicted that error terms for recognition performance increased from T1 to T2. Figure 22 schematically illustrates why the predictions of the computational model of Shanks et. al. (2003) -regarding the empirical data of Experiments 4A and 4B- may be implausible. Note that if the error term in recognition is interpreted as a threshold in the sensitivity of the explicit measure, then the computational model has to predict that the threshold increases with time (cf. Figure 2 and Figure 22). Therefore, I think that this finding represents a boundary condition for the computational model because it is no longer possible to appeal to the idea that the observed dissociations are due to error terms involved in different levels of difficulty (i.e., thresholds) for the implicit and the explicit tests.

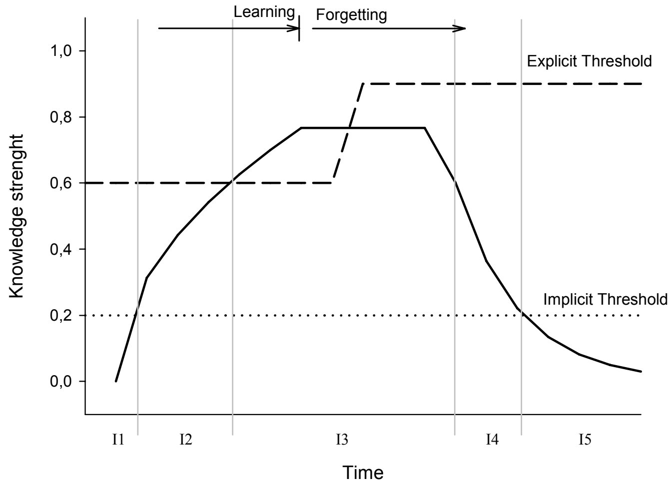

Figure 22: Hypothetical learning and forgetting for a model assuming a single knowledge strength according to the results of the simulation for Experiment 4. The dotted line represents a threshold for implicit knowledge, whereas the dashed line represents a threshold for explicit knowledge.

The most general question addressed in this dissertation is whether the evidence of different forgetting patterns for implicit and explicit knowledge provides support for the assumption of different, implicit and explicit, memory systems. According to the multiple-systems theory of implicit and explicit knowledge, implicit and explicit knowledge are supported by different memory systems. Thus, the theory can easily explain different forgetting and interference results for explicit and implicit knowledge by assuming that the explicit memory system might be more susceptible to decay and interference than the implicit memory system (e.g., Graf & Schacter, 1987). The present results appear to be consistent with this view. However, one argument usually held against this approach is that the competitive assumption of one single memory system is more parsimonious than the assumption of multiple systems. I think that the reported empirical evidence shows that single system perspectives have to work around the problem of different forgetting patterns by postulating an additional mechanism that differently translates the memory trace to overt behavior. One key question, derived from the postulation of such a mechanism, is whether this additional *ad ho*c process would require, in turn, the hypothesis of a task-dependent subsystem to explain performance on explicit tasks such as recognition. If such an approach is taken by the single-system proponents, then it would be difficult to conceptually distinguish between (1) a single system view that suggests an additional ad hoc mechanism, and (2) the multiple system views that assume *a priori* different mechanisms. Therefore, it seems to me more parsimonious the latter idea of different a priori mechanisms.

5.1 Future directions

There are two important limitations in the present studies. First, the restricted number of retention intervals (2 intervals in Experiments 1, 2, and 4A; and 3 intervals in Experiments 4B). Second, the lack of an alternative measure of explicit knowledge such as recall. In fact, an interesting empirical question would be to test the retention of implicit and explicit knowledge with more retention intervals and find the function and parameters of the curve that best describe the results. Although such an attempt was made in Experiment 4B, the small number of retention intervals did not provide sufficient data points to draw reasonably valid conclusions regarding the specific form of the forgetting curve (exponential, power, etc) for implicit knowledge.

The use of recall tests may be also implemented in order to better clarify the specific mechanisms involved in forgetting and interference of explicit knowledge. The idea is that further dissociations between two different explicit tasks such as recall and recognition may help us understand the generality of the interference hypothesis of explicit memory.

5.2 Final remarks

When I started to plan the experiments for this dissertation, I expected that the techniques used here would finally demonstrate that the partition between implicit and explicit knowledge is sound and that clear and straightforward evidence for that assumption would be found in the observation of different forgetting patterns for implicit and explicit knowledge (at least in the context of AG and SRT task). However, as the empirical research evolved, and I discovered the power and flexibility of the single-system model of Shanks et al., (2003), I changed my mind and began to think that a single-system model might be more adequate for the simple reason of applying Occam's razor. However, when I undertook a systematic review of the evidence for different forms of memory consolidation and forgetting, it appeared to me that the overwhelming majority of studies, despite many methodological and logical difficulties, in general, point out that the distinction between implicit and explicit systems is a productive one. Now, with the new evidence provided here, I believe that the distinction between implicit and explicit knowledge and related concepts such as declarative and procedural knowledge is indisputably useful. It has not only boosted research on learning and memory but it has also impregnated many different research areas of experimental psychology. Perhaps a finer functional taxonomy of knowledge may emerge, in which different forms of knowledge are not only sought as isolated compartments but also as graded functional adaptations to the environment. Often, simple dichotomous frameworks evolve into taxonomies, and then into formal descriptions of a wide spectrum of differentiated phenomena. Long-lasting discussions about the adequacy of taxonomies of learning and memory have been very useful because they possess an indisputable heuristic power and an intuitive appeal.

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List of Figures

Appendix 1

Grammatical and Ungrammatical Strings Used in Experiments 1, 2 and 3. Underlined letters from ungrammatical items indicate positions where violations to the artificial grammar (Figure 2) were introduced

Grammatical	Ungrammatical
1 JFK	J$\underline{D}$K
2 JSFDK	JSF$\underline{D}$D
3 JSKSJ	J$\underline{D}$KSJ
4 JFKSFD	JFK$\underline{K}$FD
5 JFDKKK	$\underline{D}$FDKKK
6 SFSKSJ	SFSKS$\underline{D}$
7 SJDKKKK	SJDKKK$\underline{D}$
8 SFSKJFD	SFSK$\underline{D}$FD
9 SJKSSSS	SJKSSS$\underline{K}$
10 JFKDJSK	JFKDJ$\underline{D}$K
11 SJKJFDK	SJK$\underline{D}$FDK
12 SJKSFSK	SJKSFS$\underline{F}$
13 SJKJSKS	SJKJ$\underline{D}$KS
14 SJKJSFK	SJKJSF$\underline{F}$
15 JFKDSFD	JFKD$\underline{K}$FD
16 JFKJSFK	JFKJSF$\underline{F}$

Appendix 2

In Experiment 2, I used a reduced number of items during tests. This was done in order to avoid repeating the same items before and after the retention interval. To counterbalance the presentation of items, every participant observed a different combination of new and old items. These items were randomized as shown in Table A2.

One potential problem of this procedure is that the number of items is reduced (every participant is only tested with 8 new and 8 old items at pre and post tests). In order to test whether this reduction affected the general pattern of results I ran an ANOVA for every randomization group from Experiment 1. This is to say, I simulated what would have happened if every participant of Experiment 1 had seen only half of the items according to the randomizations done for Experiment 2. In this way, it was possible to test if the reduction affected the general pattern of results of endorsement rates and reaction times.

Table A2. Distribution of new and old randomized items used in Experiment 2. For example, for randomization ID 1. ietms 1, 2, 4, 8, 9, 13 15, and 16 are selected. For randomization 2, items 3, 5, 6, 7, 10, 11, 12 and 14.

	Test Items		**Randomly selected sequences**									
ID	***Old***	***New***	***1/2***	***3/4***	***5/6***	***7/8***	***9/10***	***11/12***	***13/14***	***15/16***	***17/18***	***19/20***
1	JFKSFD	JFKJFD	1	1	1	1	0	1	1	0	0	0
2	SJDKKKK	SJDKKKF	1	0	0	0	1	0	1	1	1	0
3	JFDKKK	SFDKKK	0	0	0	0	1	0	0	0	0	0
4	SFSKJFD	SFSKSFD	1	1	0	0	0	1	0	0	0	1
5	SFSKSJ	SFSKSS	0	1	0	1	1	0	0	1	1	1
6	SJKSSSS	SJKSSSISI	0	1	1	1	1	0	1	1	1	1
7	JFKDJSK	JFKDJFK	0	1	0	1	0	1	1	1	1	0
8	SJKJFDK	SJKSFDK	1	0	1	0	0	0	0	1	0	1
9	JFK	JSK	1	1	0	1	1	1	1	0	0	1
10	SJKSFSK	SJKSFSD	0	0	0	0	0	0	0	1	1	0
11	JSKSJ	JFKSJ	0	0	1	1	0	1	1	0	0	1
12	SJKJSKS	SJKJFKS	0	0	1	0	1	0	1	0	1	0
13	SJKJSFK	SJKJSFD	1	1	0	1	1	1	0	0	1	0
14	JFKDSFD	JFKDJFD	0	0	1	1	1	1	1	1	0	1
15	JFKJSFK	JFKJSFD	1	1	1	0	0	0	0	0	0	1
16	JSFDK	JSFDF	1	0	1	0	0	1	0	1	1	0

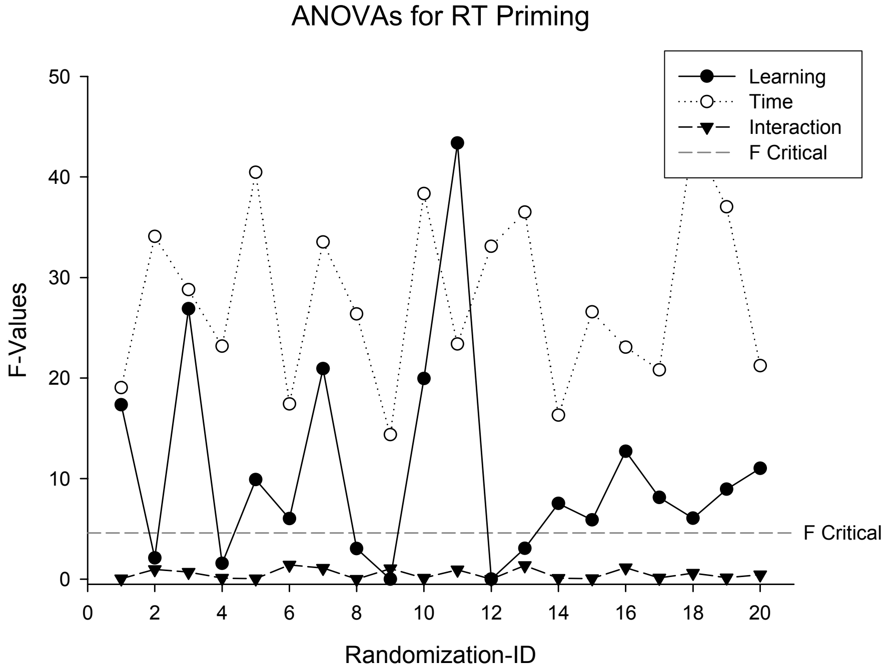

Figure 1. Results for the ANOVAs of RT priming for every randomization group. All values above the F critical indicated a significant effect.

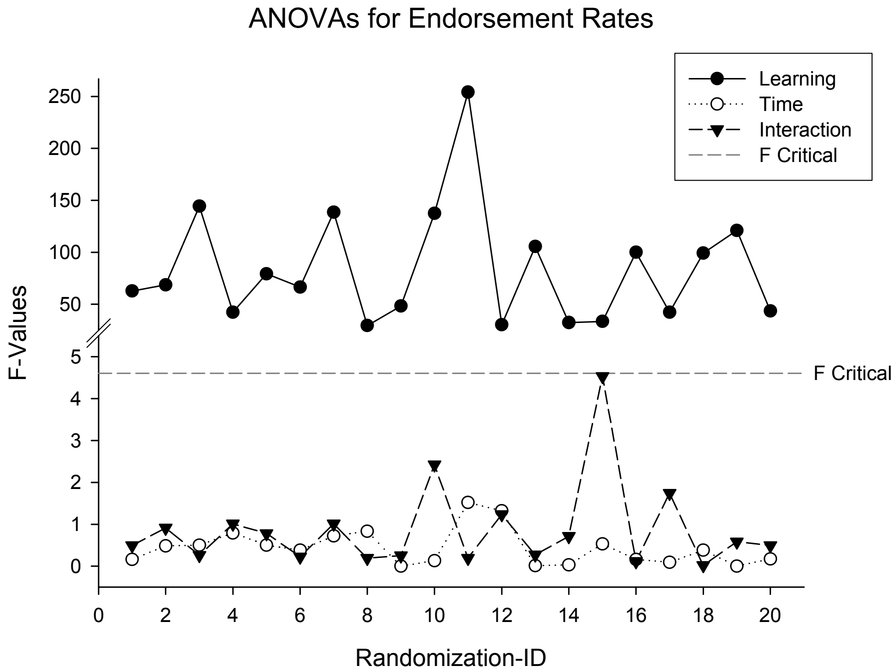

Figure 2. Results of the ANOVAs of endorsement rates for every randomization group. All values above the F critical indicated a significant effect.

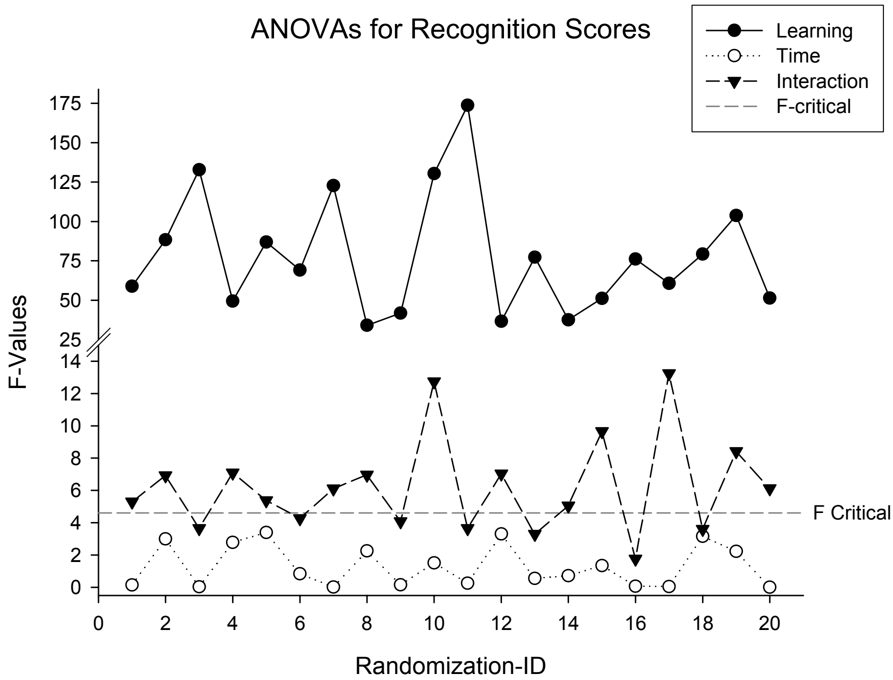

Figure 3. Results of the ANOVAs of recognition scores (including confidence ratings) for every randomization group. All values above the F critical indicated a significant effect.

Taken together the results show that, in average, reducing the number of test items would not have change the main outcomes neither for the explicit knowledge assessment (Recognition Scores, Figure 1) nor for the implicit knowledge assessment (RT Priming, Figure 3).

Appendix 3

I explain here the procedure to obtain the formulas dRT(predicted) and dREC(predicted) used as a basis for the simulations.

The model of Shanks et al. (2003) is based on two formulas to compute priming and recognition:

$$RT = b + 100\,(1-f) + 500\, e_{rt} \qquad (1)$$

$$J = 2\, f + e_j + 1 \qquad (2)$$

In practice, it is necessary to simulate RTs and recognition scores for new and old items based on different familiarity values for new (.4) and for old items (.6).

$$RT_{new} = b + 100\,(1-f_{new}) + 500\, e_{rt}\ , \qquad (3)$$

$$RT_{old} = b + 100\,(1-f_{old}) + 500\, e_{rt,}\ , \qquad (4)$$

$$J_{new} = 2\, f_{new} + e_j + 1, \qquad (5)$$

$$J_{old} = 2\, f_{old} + e_j + 1, \qquad (6)$$

I used the model of Poldrack and Logan (1997) to convert the predicted values of the model to the same scale. The model of Poldrack and Logan (1997) applied to RTs indicates that the mean RTs for new items should be subtracted from the mean RT for old items and that the corresponding standard deviations for each mean should be known:

$$dRT = \frac{RT_{new} - RT_{old}}{\frac{\sigma RT_{old}}{2} + \frac{\sigma RT_{new}}{2}}, \qquad (7)$$

Similarly, the mean recognition scores for old items should be subtracted from the mean recognition scores for new items and the corresponding standard deviations for each mean should be known.

$$dJ = \frac{Jold - Jnew}{\frac{\sigma J_{old}}{2} + \frac{\sigma J_{new}}{2}}, \qquad (8)$$

The means required in Formulas 7 and 8 are provided in Formulas 3, 4, 5, and 6.

To obtain the standard deviations required in Formulas 7 and 8 (to compute the predicted values of mean RTs and mean J), I used the principle of propagation of uncertainty. Because the standard deviations of the error terms for RT (σe_{rt}), recognition (σe_{j}), and familiarity (σf) are provided in the original model of Shanks et al. (2003), it is possible to determine the value of the standard deviation of the mean RTs and mean recognition as follows:

$$\sigma RT = \sigma f + 5\sigma e_{rt}, \qquad (9)$$

$$\sigma J = 2\sigma f + \sigma e_{J}, \qquad (10)$$

The next step was to replace Formulas 3, 4, and 9 into Formula 7; and Formulas 5, 6, and 10 into Formula 8, respectively:

$$dRT = \frac{[\mathrm{b} + 100\,(1 - f_{\mathrm{new}}) + 500\ \mathrm{e_{rt}})] - [\mathrm{b} + 100\,(1 - f_{\mathrm{old}}) + 500\ \mathrm{e_{rt}}]}{\frac{\sigma f + 5\sigma e_{rt}}{2} + \frac{\sigma f + 5\sigma e_{rt}}{2}}$$

$$dJ = \frac{(2\,f_{\mathrm{old}} + \mathrm{e_j} + 1) - (2\,f_{\mathrm{new}} + \mathrm{e_j} + 1)}{\frac{2\sigma f + \sigma e}{2} + \frac{2\sigma f + \sigma e_{J}}{2}}$$

The simplified outcome of the above formulas constitutes the new Formulas 11 and 12 used to compute the predicted values of implicit (dRT) and explicit (dJ) knowledge involving the full set of assumptions implied by the model of Shanks et. al (2003).

$$dRT(predicted) = \frac{f_{\mathrm{old}} - f_{\mathrm{new}}}{\sigma f + 5\,\sigma e_{\mathrm{rt}}}, \qquad (11)$$

$$dJ(predicted) = \frac{2(f_{\mathrm{old}} - f_{\mathrm{new}})}{2\sigma f + \sigma e_{\mathrm{j}}}, \qquad (12)$$

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Eidestattliche Erklärung

Hiermit erkläre ich, Ricardo Tamayo, dass die vorliegende Dissertation von mir selbständig und ohne unerlaubte Hilfe angefertigt wurde.